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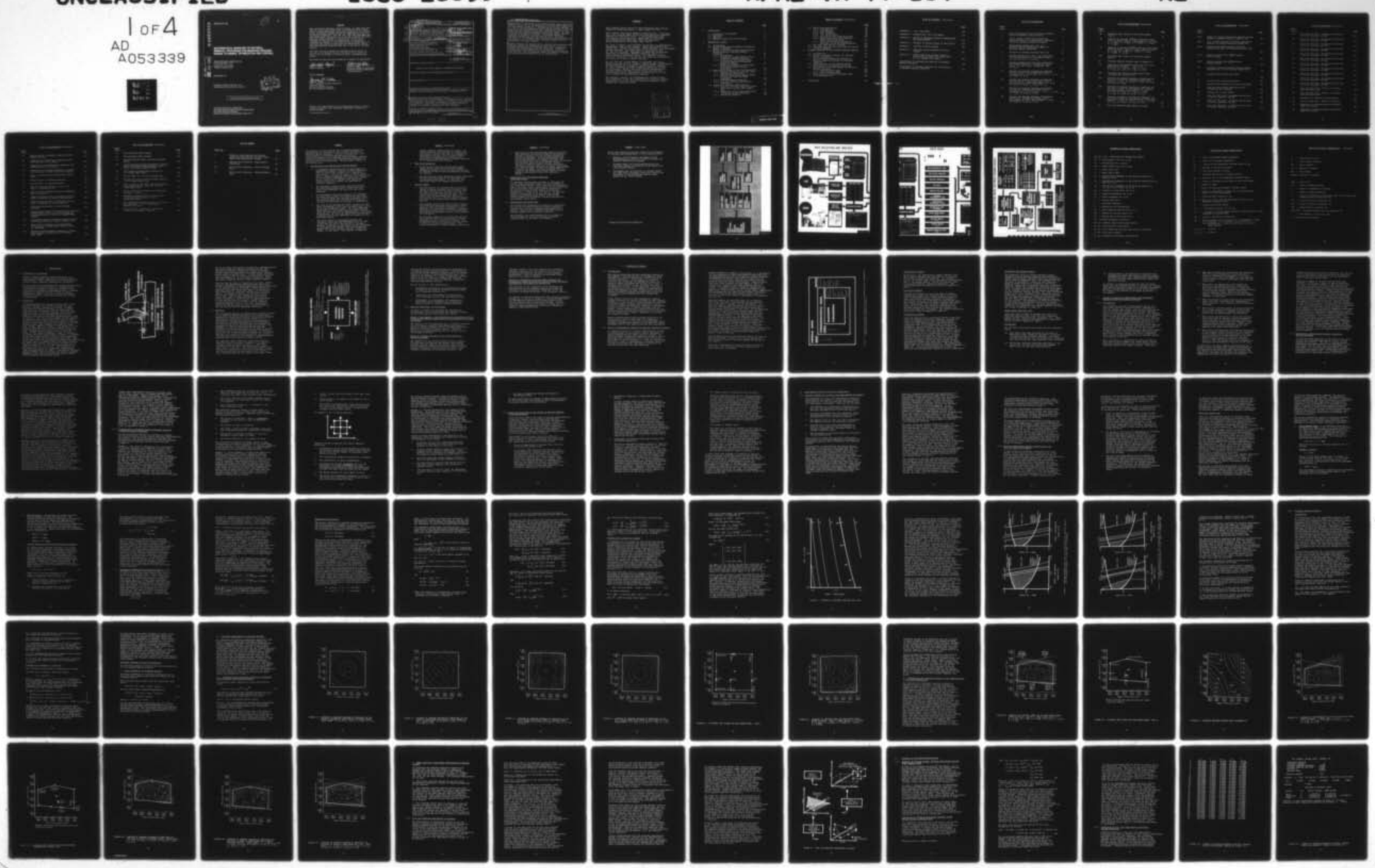

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AFML-TR-77-154

MATHEMATICAL MODELING OF MATERIAL REMOVAL PROCESSES FOR IMPROVED PROCESS DESIGN, PLANNING, OPTIMIZATION AND CONTROL

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AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

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Results of work for the development of methodologies for mathematical modeling and economic analysis of material removal processes are presented. Initially, an extensive literature review was conducted to identify the major unsolved problem areas and to examine the necessary techniques for their solution.

The major problems identified were: (1) the selection of levels and positions of independent variables during the planning of

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experiments; (2) definition of the working region within which the model is valid, and (3) incorporation of variable radial depth and/or feed during a given cut. A methodology for solving problems (1) and (2) was developed and verified through analysis of available machining data from end milling tests (Contract No. F33615-74-C-5025) and from turning (Contract No. F33615-73-C-5180). A series of end milling tests with variable radial depth and/or feed were conducted to determine the effect of in-process changes in machining variables on tool wear and tool life. Shop floor validation of the laboratory data was carried out by observing the end milling of an airframe part at McDonnell Douglas Aircraft Corporation, St. Louis, Missouri.

Economic analysis for process design, planning and optimization was conducted through the development of macro-economic and micro-economic models. The macro-economic models were intended for preplanning, value analysis and cost estimation. The micro-economic models were intended for detailed process planning and cost analysis. The micro-economic model was applied to evaluate and optimize process parameters for an airframe part.

FOREWORD

This progress report covers all work performed under Contract F33615-76-C-5254 from April 1, 1976 to April 15, 1977.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio, was initiated under FY1457 Air Force Materials Laboratory Contract No. F33615-76-C-5254. It was accomplished under the technical direction of Dr. Harold Gegel of the Metals and Ceramics Branch (AFML/LLM), Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

Dr. Vijay A. Tipnis, Vice President and Director of Manufacturing Technology is the project manager. Others who worked on the project are: Messrs. Steven Vogel, Steve Buescher, John Christopher and Ray Garrison. The consultants for this project were Dr. S.M. Wu, Professor, Department of Mechanical Engineering, University of Wisconsin, Madison, Wisconsin, and Dr. R.E. DeVor, Associate Professor, and Mr. W.J. Zdeblick, Research Assistant, Department of Mechanical and Industrial Engineering, University of Illinois, Urbana, Illinois.

Mr. R.F. Mueller, Branch Manager of Equipment and Process Engineering, and Mr. W.R. Franklin, Branch Manager, Manufacturing Methods Engineering of McDonnell Douglas Aircraft Company, St. Louis, Missouri provided valuable guidance and critique to the program. Messrs. Mike Graff and Ben Manshenross of the same company provided guidance during the shop floor observations, and Mr. Ramon Datsal provided data on NC cuts on an airframe for microeconomic analysis.

The concepts, results, and recommendations presented under this program are solely the responsibility of Metcut Research Associates Inc. to the extent of the work statement of the Contract No. F33615-76-C-5254.

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SUMMARY

The objective of this project was to develop concepts and methodologies for mathematical and economic modeling of material removal processes. This is a crucial step in the transformation of aerospace manufacturing from an "experienced-based" to a "knowledge and data-based" industry. Concepts and methodologies were developed and validated for airframe end milling operations. The principal findings of the project were:

A. Methodologies for Mathematical Process Models:

1. A recommended methodology for the development of mathematical models of material removal operations such as end milling, turning, etc. consists of three stages: (1) initial tests to obtain viable data to begin mathematical modeling; (2) construction of the feasible experimental or production region, and (3) selection of further tests within the feasible region to optimize the experimental objective function.

2. The desirable feasible region should be defined by establishing probabilistic constraints (e.g., 90% or 95% confidence) for tool life and other responses.

3. An experimental objective function, the D-Optimal criterion which places each additional test point at a location where the variance is greatest within the working region until the desirable level of variance and precision is achieved, is recommended.

4. The form of the mathematical model suitable for the above methodology is the first or second order linear in the log transformed space. The log transformed space appears to be appropriate for model building since the tool life can be represented by a log normal distribution, and since the application of statistical techniques is greatly simplified as compared to the nonlinear models.

5. The major sources of discrepancy between the laboratory tests and shop performance are (a) heat-to-heat and lot-to-lot variability in the work material (titanium, in this case) and (b) differences in the machine tool-fixture-cutting tool-workpiece dynamic and static rigidity (end mill cutter and holder, in this case). This subject is important

enough to deserve investigation of its own. The limited number of tests on item (a) conducted in this project indicate that there is a significant difference in the tool life of Ti-6Al-4V heats. This difference appears to be related to the differences in thermo-mechanical treatment received by the titanium bars and forgings.

B. Shop Floor Validation

1. NC and AC cuts involving variable radial depth and/or feed or other cutting variables produce cummulative degradation in tool wear and tool life as compared to cuts in which the machining variables are constant.

2. The tool life and cutter performance limits established through laboratory tests can be correlated with the production performance. In this case, the latter was found to be somewhat conservative.

C. Economic Models

1. The basic form of the economic model for material removal processes includes terms related to setup and other constant times and costs, feeding time and costs, tool changing time and cost, tool reconditioning cost, and material costs. Each of these terms includes mathematical models for cutting rate, tool life, material and cut geometry. This form of the economic model enhances tradeoff analysis.

2. Macro-economic models that relate process rates to cost drivers are obtained from the basic economic model when only preliminary information on part geometry, cuts and process parameters is available. Such models are applicable to evaluate processing alternatives during process design, cost estimation and preplanning.

3. Micro-economic models can be constructed from the basic economic model for optimization of process parameters and for detailed cost analysis. The mathematical model of the material removal process is linked to the micro-economic model. This enables comprehensive process parameter optimization.

4. Application of the micro-economic models to detailed cost estimation and process parameter optimization provides a valuable tool for process planning and overall optimization. This was demonstrated when the process parameters for several different end milling operations on an airframe part were investigated and optimized using the micro-economic models. The cost of material removal in these operations (excluding constant costs such as setup, load/unload, etc.) can be reduced by about 30% through optimization of speeds and feeds. The micro-economic model is linked to the mathematical process model to conduct parameter optimization within the operability region.

D. Overview of the "Data-Based" Machining Technology System

The schematic diagram shown in Figure I, describes the overall interrelationships among the various phases of the "data-based" system: data collection and mathematical model, data base, macro-economic model and cost estimation, and micro-economic model and parameter optimization. The details of each of these phases are described schematically in Figures II, III, and IV. An important feature of the system is the flow of data through analysis and modeling stages before it enters the economic models for evaluation of process alternatives and parameter optimization.

E. Applications and Future Work

The concepts and methodologies presented are applicable not only to the specific material removal operations investigated, but also to manufacturing operations in general. Application to computer aided manufacturing programs appears to be especially promising.

Specifically, this system should serve as a model for the development of practical machining technology systems within the Air Force, and industry.

SUMMARY (continued)

Future work should be directed towards the development of concepts and methodologies in the following areas:

1. Material, M-F-T-W* system, and emperical and phenomenological models for material removal and material deformation processes.

2. Economic models for design/manufacturing cost interface through an extension of the macro- and micro-economic models.

3. Development and verification of economic models for sheet metal processes within the scope of the objectives of the Integrated Computer Aided Manufacturing (ICAM) program.

* Material-Fixture-Tool-Workpiece

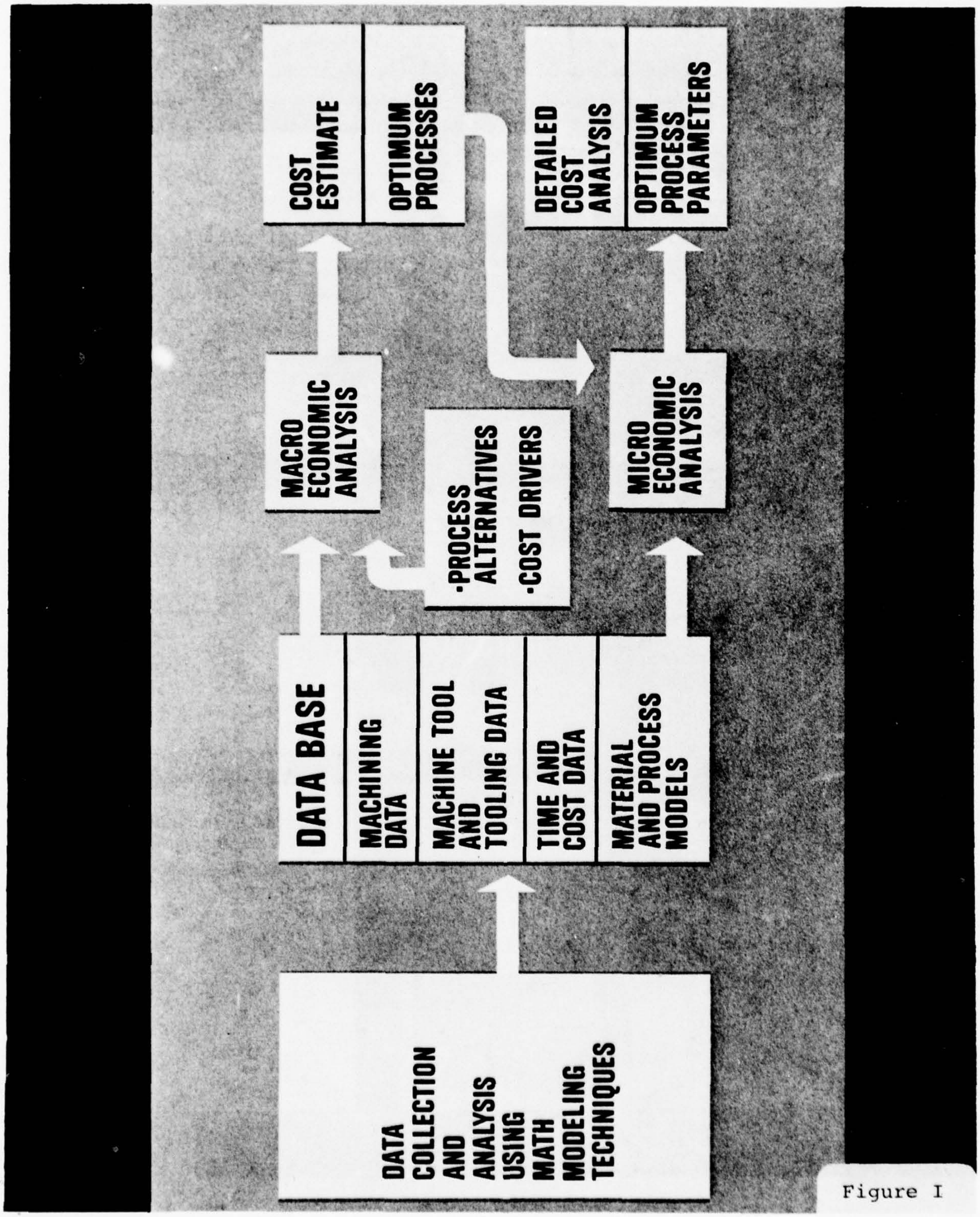
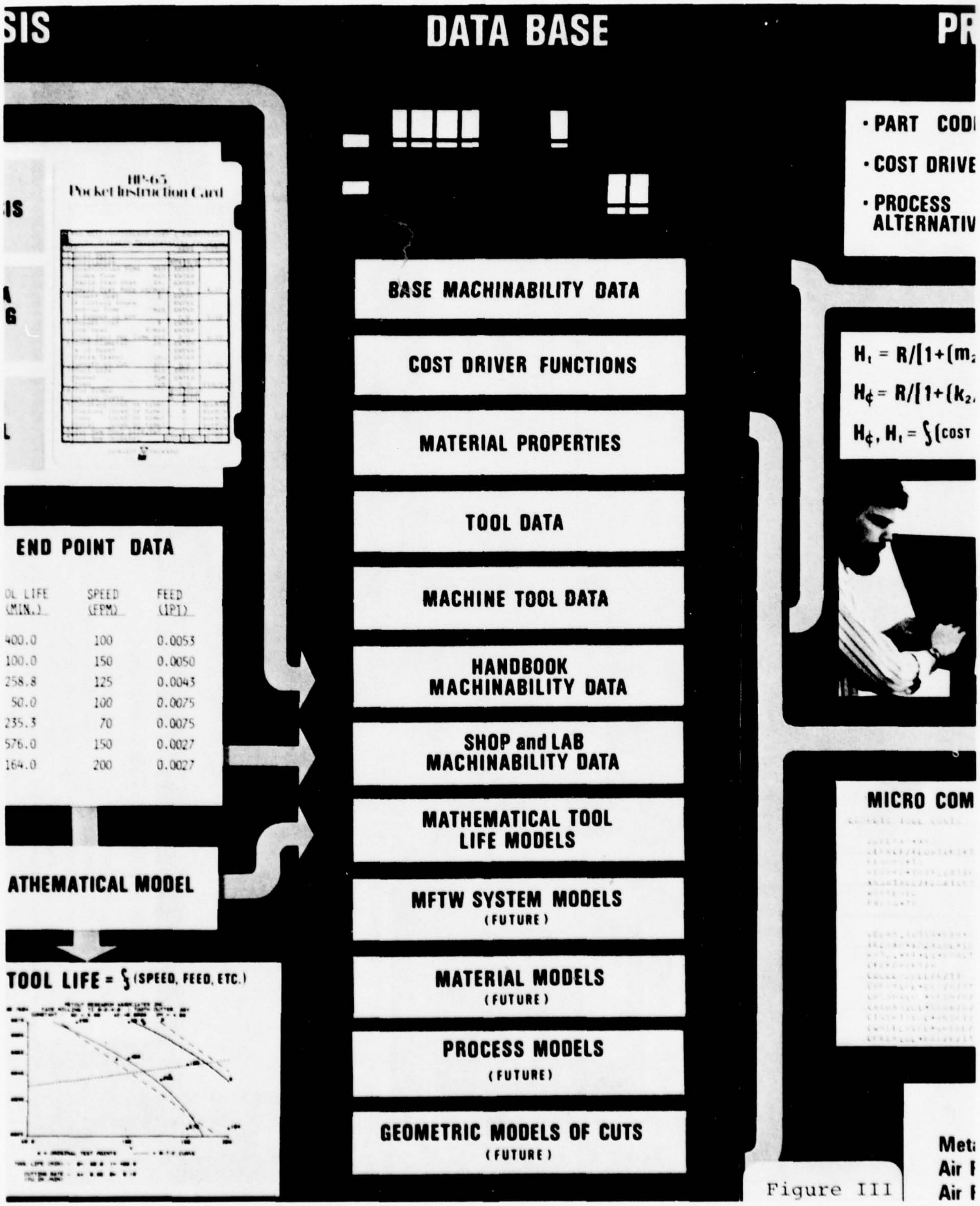

DATA COLLECTION AND ANALYSIS USING MATH MODELING TECHNIQUES
DATA BASE
MACHINING DATA
MACHINE TOOL AND TOOLING DATA
TIME AND COST DATA
MATERIAL AND PROCESS MODELS
•PROCESS ALTERNATIVES
•COST DRIVERS
MACRO ECONOMIC ANALYSIS
MICRO ECONOMIC ANALYSIS
COST ESTIMATE
OPTIMUM PROCESSES
DETAILED COST ANALYSIS
OPTIMUM PROCESS PARAMETERS

Figure I

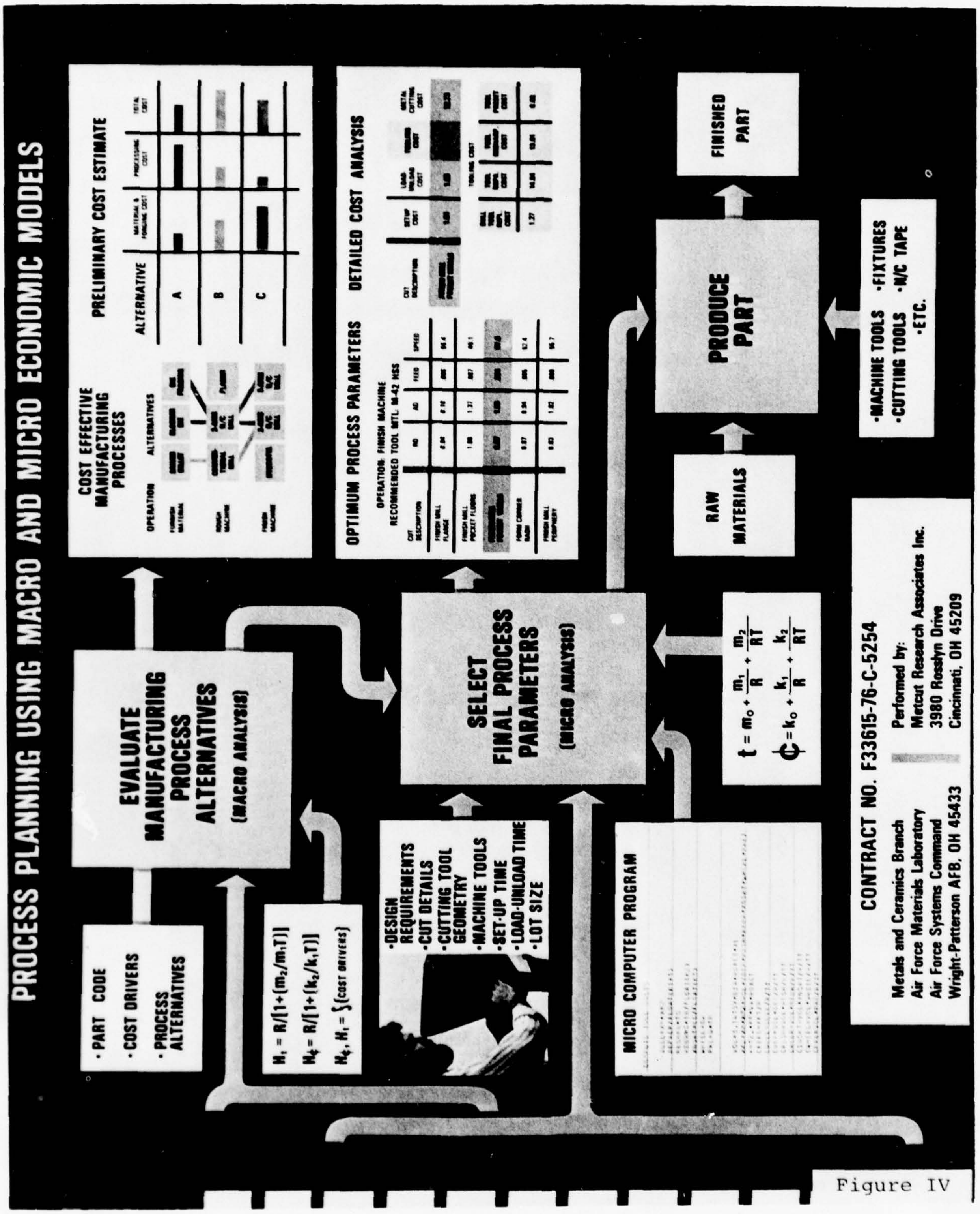

DATA COLLECTION AND ANALYSIS
HANDBOOK
LAB
SHOP
PROGRAMMABLE CALCULATOR
COST ANALYSIS
OPTIMA SEEKING
MATH MODEL
HP-65 Pocket Instruction Card
MANUAL DATA COLLECTION
AUTOMATED DATA COLLECTION (FUTURE)
END POINT DATA
TOOL LIFE (MIN.) SPEED (FPM) FEED (IPT)
400.0 100 0.0053
100.0 150 0.0050
258.8 125 0.0043
50.0 100 0.0075
235.3 70 0.0075
576.0 150 0.0027
164.0 200 0.0027
TOOL LIFE END POINT CALCULATION
MATHEMATICAL MODEL
TOOL LIFE = ∫ (SPEED, FEED, ETC.)

Figure II



OL LIFE (MIN.)	SPEED (FPM)	FEED (IPT)
400.0	100	0.0053
100.0	150	0.0050
258.8	125	0.0043
50.0	100	0.0075
235.3	70	0.0075
576.0	150	0.0027
164.0	200	0.0027

Figure III


PROCESS PLANNING USING MACRO AND MICRO ECONOMIC MODELS
•PART CODE
•COST DRIVERS
•PROCESS ALTERNATIVES
EVALUATE MANUFACTURING PROCESS ALTERNATIVES
(MACRO ANALYSIS)
COST EFFECTIVE MANUFACTURING PROCESSES
OPERATION
ALTERNATIVES
PRELIMINARY COST ESTIMATE
ALTERNATIVE
A
B
C
$H_t = R/[1+(m_2/m_1T)]$
$H_\phi = R/[1+(k_2/k_1T)]$
$H_\phi, H_t = \int(\text{COST DRIVERS})$
•DESIGN REQUIREMENTS
•CUT DETAILS
•CUTTING TOOL GEOMETRY
•MACHINE TOOLS
•SET-UP TIME
•LOAD-UNLOAD TIME
•LOT SIZE
SELECT FINAL PROCESS PARAMETERS
(MICRO ANALYSIS)
OPTIMUM PROCESS PARAMETERS
DETAILED COST ANALYSIS
$t = m_o + \frac{m_1}{R} + \frac{m_2}{RT}$
$\phi = k_o + \frac{k_1}{R} + \frac{k_2}{RT}$
MICRO COMPUTER PROGRAM
RAW MATERIALS
PRODUCE PART
FINISHED PART
•MACHINE TOOLS
•CUTTING TOOLS
•FIXTURES
•N/C TAPE
•ETC.
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Metals and Ceramics Branch
Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson AFB, OH 45433
Performed by:
Metcut Research Associates Inc.
3980 Rosslyn Drive
Cincinnati, OH 45209

Figure IV

MATHEMATICAL MODELS NOMENCLATURE

b_0, b_1,...b_{11} = coefficients of mathematical models

AD = axial depth of cut (in. or mm)

R = cutting rate (cu. in./min.)

RD = radial depth of cut (in. or mm)

f = feed (ipr or ipt)

v = speed (fpm or mpm)

F_x = cutting force component in the direction parallel to feed (lb. or N)

F_y = cutting force component in the direction perpendicular to feed (lb. or N)

F_z = cutting force component in the direction parallel to the axis of the cutter (lb. or N)

F_R = resultant cutting force (lb. or N)

F_t = tangential component (lb. or N)

F_r = radial component (lb. or N)

t = cutting time (min.)

C = cost/piece ($/piece)

P = production rate (pieces/hour)

FL = flute length of milling cutter (in.)

DM = diameter of milling cutter (in.)

UN = uniform wear on the cutter (in.)

S.f. = surface roughness (microinch)

m_0, k_0 = constant time and cost coefficients

m_1, k_1 = feed time/cost coefficients

m_2, k_2 = tool change and cost/edge time and cost efficients

T = TL = Tool Life (minutes)

H_t, H_c = productivity functions, time and cost

STATISTICAL MODELS NOMENCLATURE

$\underline{b}$ = vector of estimated model parameters

$\underline{\beta}$ = vector of true model parameters

$\underline{\eta_i}$ = vector of true dependent variable value for $\underline{x_i}$

S^2 = observed or estimated variance

σ^2 = true (but unknown) variance

σ = standard deviation of a random variable

$\underline{x_i}$ = vector of i^{th} in the independent variable space

$\underline{\varepsilon}$ = vector of residual errors based on the fitted model

N = number of tests

$\underline{Y}$ = matrix of observed dependent variable values

$\underline{X}$ = matrix of independent varables for the experimental design (for the fitted model)

$\hat{Y}_i$ = predicted mean response at $\underline{x_i}$

$\bar{Y}_i$ = mean of g future observed responses to occur at $\underline{x_i}$ (dependent variable values)

$\underline{V}$ = variance-covariance matrix

w_i = i^{th} weighting factor in $\underline{V}$ at $\underline{x_i}$

σ_i^2 = variance of the dependent variable at the i^{th} point in the independent variable space

R^2 - multiple correlation coefficient

S_p^2 = pooled estimate of the variance of the dependent variable
(i) estimates σ^2 if variance is constant over $\underline{X}$
(ii) estimates σ_a^2, a scaling factor used in weighted least squares

$F_{v_1, v_2, \alpha}$ = (F-test)

$t_{v, 1-\alpha/2}$ = (t-test)

STATISTICAL MODELS NOMENCLATURE (continued)

Q = (Burr-Foster Q test)

Z = (Unit normal variable)

SS = sum of squares

d.f. = degrees of freedom

MS = mean square

ANOVA= analysis of variance

LOF = lack of fit

CCD = central composite design

h = number of independent variables

p = number of model parameters

α = level of statistical significant error of the first kind (commonly 0.25/.10/.05/.025/.01)

"$\hat{m}$" = estimated value of statistic "m"

"$\underline{m}$" = vector or matrix of quantity "m"

"$\bar{m}$" = sample mean of statistic "m"

VAR ("m") = variance estimate for the statistic "m"

λ = the change in tool failure rate

k = coefficient of variation

1. INTRODUCTION

1.1 Statement of the Problem

Material removal processes such as machining and grinding lack adequate quantitative characterization. This presents a major impediment to the improvement of process design, planning, optimization and control.

The necessity for transforming the aerospace manufacturing industry from "experience-based" to "knowledge and data-based" has become increasingly evident with the introduction of computer aided manufacturing. Adequate quantitative characterization in terms of usable mathematical models of the specific material removal processes involved is the first crucial step in the transformation.

1.2 Background

The important material removal processes used in the aerospace industry are turning, end milling, face milling, drilling, tapping and grinding. Although these material removal processes are significantly different from one another, they all share some basic characteristics. This fact has been recognized for some time. The basic characteristics of the chip removal process can be described schematically as shown in Figure 1. Here the required amount of work material is removed by the cutting tool in the form of chips. During this process, the cutting tool wears in two main regions: crater and wearland. Chip removal is achieved through intense shear deformation within the shear zone. Another important feature is the formation of the built-up edge, which is a highly deformed portion of workpiece material adhering to the tip of the cutting tool. Unstable built-up edge is one of the prime causes of poor surface roughness. About 75 percent of the energy generated during material removal is consumed in the shear zone, regions 1 and 2, and the remaining energy is consumed at the frictional interfaces, 3 and 4. The shear zone and frictional interfaces characteristically have high values of combined shear and normal stresses. The shear zone involves intense shear deformations at strains as high as 5 in./in. and strain rates in the range of 10^3 to 10^5 in./in./sec. The temperature in the shear zone and at the frictional interfaces may range from about 800°F to 1400°F. The machined workpiece surface assumes certain tolerance and surface roughness, depending on the operating conditions such as speed, feed and machine tool characteristics.

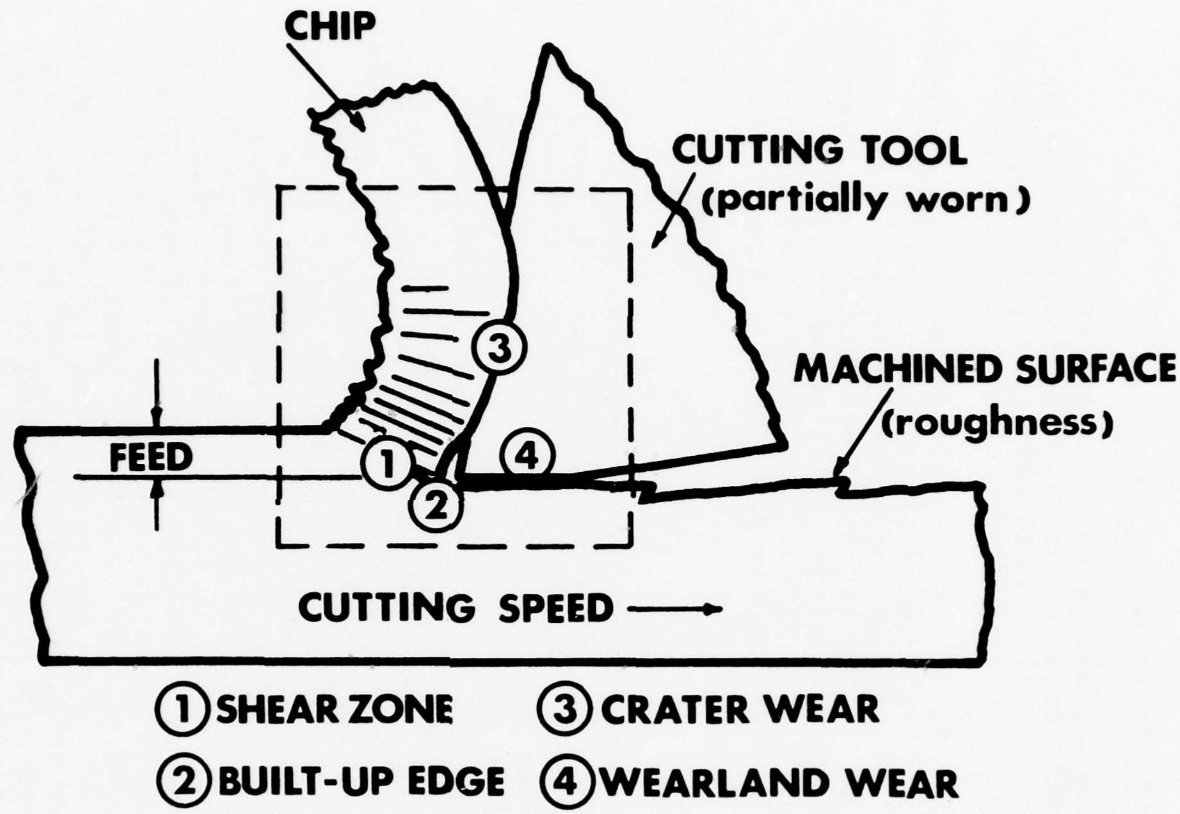


Figure 1 - BASIC CHARACTERISTIC OF THE MATERIAL REMOVAL PROCESS--SCHEMATIC REPRESENTATION

One of the major difficulties in applying a phenomenological approach to material removal processes has been that the material behavior relevant to a material removal process cannot be reproduced and studied except through actual material removal tests. In other words, meaningful data on material behavior such as stress-strain, strain rate and temperature as they relate to material removal operations cannot be obtained from mechanical testing.

Over the last 90 years of research in this area, several different phenomenological approaches have been tried for the development of usable quantitative characterizations of the material removal processes. Among some of the important approaches tried have been: (a) mechanics of chip formation; (b) plasticity analysis using slipline theory, (c) thermal analysis, (d) tool wear theories, and (e) metal physics and dislocation study of the shear zone. Each of these approaches has produced useful information; however, none of these approaches to date has been able to produce a usable theory or relationships that can be used to predict important machining responses such as tool life, as-machined surface finish and accuracy, given the work material, the cutting tool and the operating conditions.

1.3 Approach

The recommended approach for quantitative characterization of the material removal process is that of developing mathematical relationships between the machining response and operating conditions directly through a set of experiments. The approach involves the application of statistically planned experiments and the development of statistically valid, deterministic and probablistic mathematical models of material removal processes. The mathematical relationships developed through this approach are directly applicable to the material removal processes used in the aerospace industry. It should be noted that the information gained through the recommended approach will provide valuable guidelines for pursuing the long range objective of developing a phenomenological understanding of the material removal process.

The important input conditions, controlling factors, operating factors and output response of the material removal process are shown in Figure 2. The input consists of the machining conditions such as speed, feed, depth of cut, etc. The controlling factors which dictate the constraints as well as the operating region are those resulting from the machine tool, cutting tool, workpiece material and cutting fluid used. These

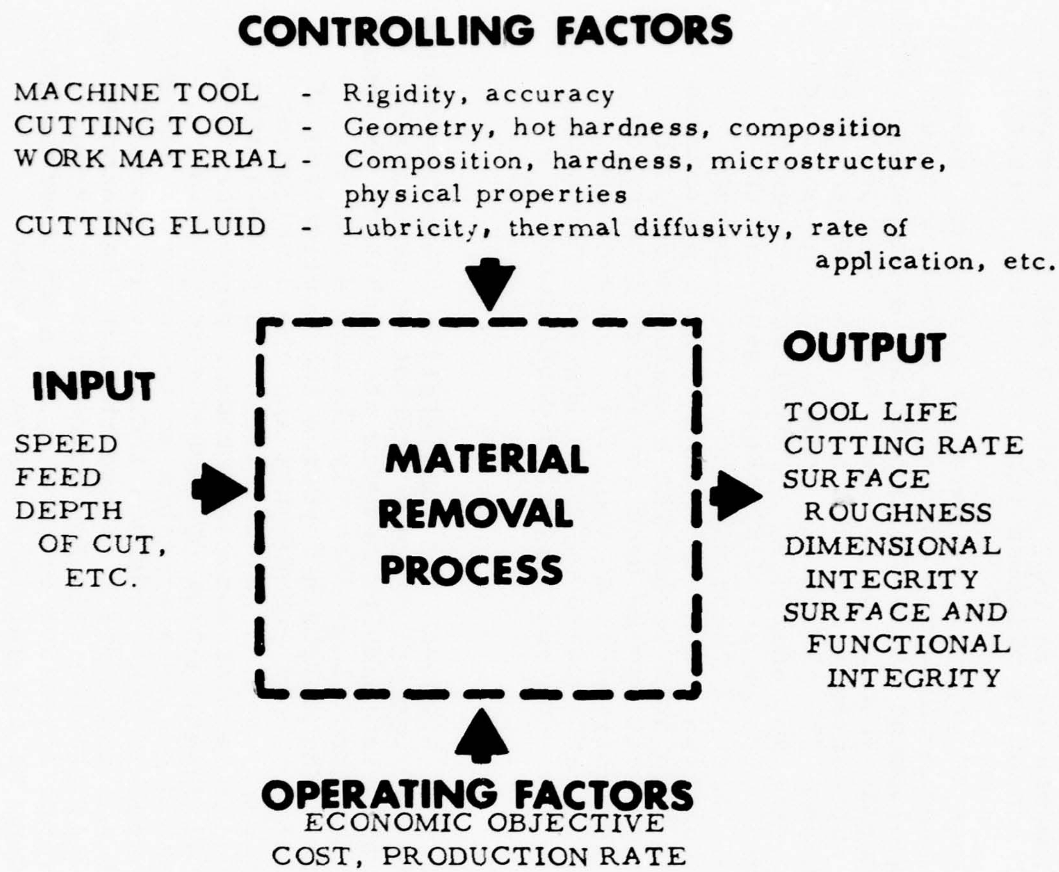


Figure 2 - INPUT, OUTPUT, CONTROLLING FACTORS, AND OPERATING FACTORS FOR QUANTITATIVE CHARACTERIZATION OF MATERIAL REMOVAL PROCESS

controlling factors can be characterized quantitatively in terms of several pertinent aspects. The process is also guided by the operating factors such as an economic objective in terms of cost and production rate. The output of the process is in terms of machining response such as tool life, material removal rate (cutting rate), cutting forces, surface roughness, dimensional tolerance and surface integrity.

The key factors in this approach are:

1. Mathematical description of the experimental space in terms of the range of variables such as speed, feed, workpiece hardness, etc.

2. Planning of the least number of statistically valid experiments within the experimental space.

3. Development of a methodology for deterministic, statistical and/or probabilistic mathematical models relevant to material removal processes.

1.4 Specific Objectives of the Program

In order to develop and introduce the mathematical relationships into aerospace material removal processes, the following specific objectives were chosen:

Phase I: Development of the Methodology for Mathematical Model Building With Specific Application to End Milling of Airframe Structures

The objective of the methodology was to develop techniques for statistically planning experiments applicable to material removal processes and for building mathematical models of the material removal process. Specific application of the methodology was for the end milling of airframe structures.

Phase II: Economic Analysis of the Total Materials Processing System

The objective of the economic analysis was to identify the important cost factors and process alternatives, starting from the shape of the initial blank through various materials processing operations used to produce aircraft structures such as forging or casting, heat treatment, machining, grinding and finishing. The

important aspect of the cost analysis was to develop suitable approaches for the evaluation of the various processing alternatives available to the aerospace manufacturer. Such an analysis was performed either manually or by using a computer.

Phase III: Validation of the Economic Analysis and Mathematical Model Building for Process Design, Planning, Optimization, and Control of End Milling

The objective of the validation was to determine the applicability of the economic analysis performed and the model building methodology formulated to the end milling of airframe structures in the aerospace industry.

In closing, it should be noted that this project represented perhaps one of the first attempts to develop methodologies for mathematical modeling and economic analysis with specific application to production problems. Indeed, continued future efforts are needed to reduce the full impact of these methodologies within the framework of computer aided manufacturing.

2. MATHEMATICAL MODELS

2.1 Introduction

This section describes the work undertaken towards the development of the methodology for mathematical model building with specific application to end milling of airframe structures. In this phase, an extensive review of the literature on mathematical models for material removal processes was carried out in order to determine what different forms of models have been attempted in the past. At the same time, a review of the literature on statistical methods of experimental design and mathematical model building that have been applied to material removal processes was carried out to determine what methodologies have already been attempted.

Since several statistical and mathematical computer program libraries are readily available on most computer networks, a brief review of these programs was undertaken to determine which programs and subroutines could be useful in conducting statistical planning of experiments in model building and in drawing inference from the models. Various approaches to model building were also initiated using the test data available in the literature and Air Force project reports, especially on Contract No. F33615-74-C-5025.

Based on observations during airframe end milling and on the work to date on this phase, the important problems that must be solved for the establishment of a systematic mathematical methodology for material removal processes used in this application have been identified.

2.2 Review of Mathematical Models For Material Removal Processes

As stated in Section 1.2, despite some progress towards an understanding of the material removal phenomena, no useful phenomenological models have yet evolved. On the other hand, an empirical approach to model building which was first introduced by F.W. Taylor (1907) has flourished to the point where it is ripe for application. With this in mind, a comprehensive literature review of the empirical models was undertaken to determine the different forms that have been developed.

Before presenting a summary of the review, it is worthwhile to focus attention on the relationship between empirical and phenomenological models for material removal processes. Phenomenological models, like Newton's laws of motion or Einstein's relativity equation, are models that are based on cause and effect relationships. These relationships have been supported by experiments in which the uncontrolled variations are small compared with the effects to be expected when a change is imposed on the system. In material removal, possible phenomenological models will relate stress, strain, strain rates, temperatures and workpiece and tool physical and chemical properties, such as thermal diffusivity, specific heat, etc., to the rate of tool wear, surface topography of the machined surface, etc.

Empirical models, on the other hand, are introduced when cause and effect relationships are not expected, due to the lack of insight into the phenomenon. In material removal, empirical models are used to express observed relationships between machining conditions such as speed, feed, depth of cut, etc., and the machining responses such as tool life, cutting forces, surface finish, etc. The relationship between empirical and phenomenological models can be expressed by the block diagram shown in Figure 3, the empirical view being coarser and less exact than the phenomenological. Yet, empirical models can be applied directly to improve, control and optimize material removal operations since their input and output parameters play an important role in the economics of such operations. Great care, however, needs to be exercised in developing and in using empirical models since the effects under investigation can become comparable with the uncontrolled variations, and there is a danger of extrapolating beyond the model's range of validity.

The following review of the empirical models for material removal processes is based on a critical analysis of the references listed in the bibliography at the end of this report.

Since the introduction of the first empirical model by F.W. Taylor, the following different categories of models have been introduced.

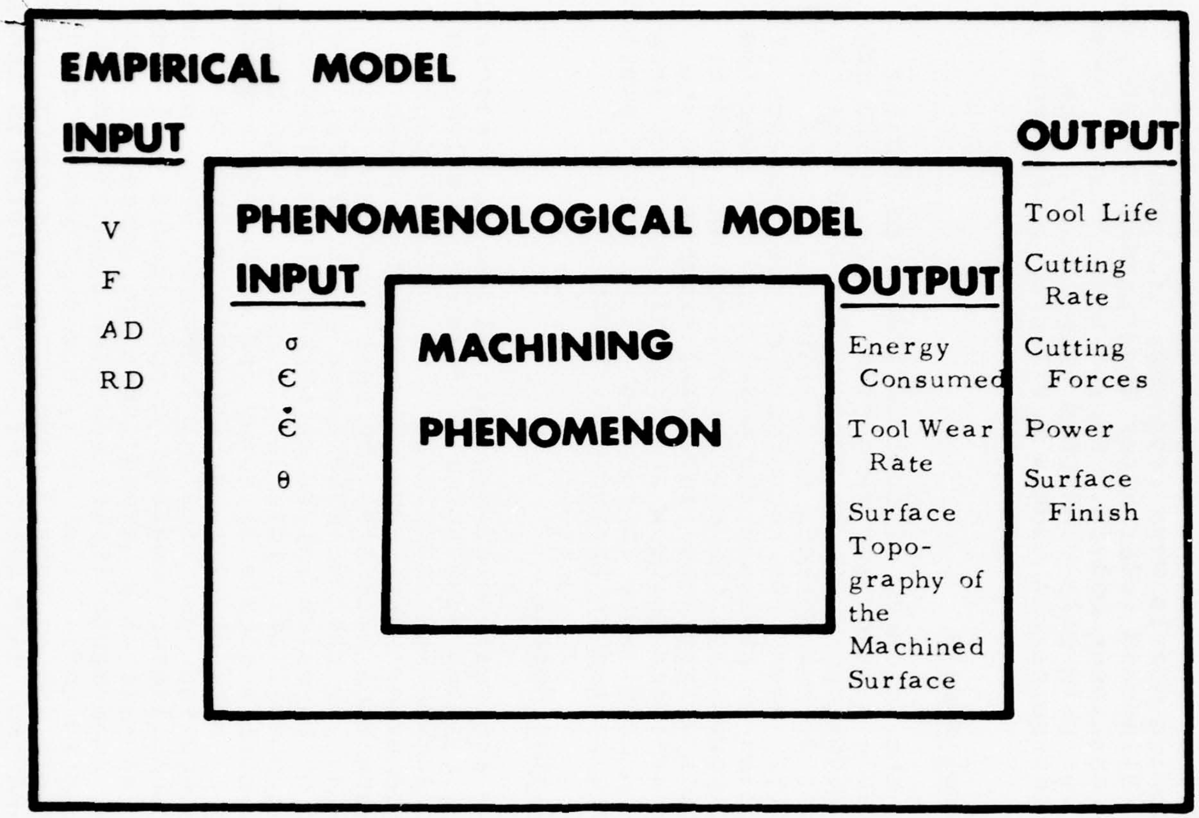


Figure 3 - RELATIONSHIP BETWEEN EMPERICAL AND PHENOMENOLOGICAL MATHEMATICAL MODELS OF MATERIAL REMOVAL OPERATIONS

Deterministic Models

Historically, the deterministic models appeared from about 1900 to the mid- and late 1960's. In this era, the following models were proposed: (a) extended-Taylor, (b) second order after logarithmic transformation, and (c) non-linear models. During this period, model fitting was primarily conducted graphically. The various deterministic models are listed in Appendix A, Table I.

Statistical Models

Although the tendency of tool life data to exhibit considerable scatter was recognized prior to the mid 1950's, researchers in the period 1950-1970 began to apply statistical methods to measure the degree of variability. Also, the techniques of least-square fits were applied to generate the model from the experimental data. Importantly, the statistical methods such as factorial and fractional-factorial experiments and variance analysis to draw statistical inference from the fitted model were introduced. The various statistical models are listed in Appendix A, Table II.

Probabilistic Models

Since the application of statistical models, especially those for drawing statistical inference, involved an implicit assumption about tool life distributions within the experimental space, researchers began to investigate tool life distributions to verify this assumption. By the mid-1960's and early 1970's, the concepts of Bayesian inference were being applied to develop probabilistic tool life models. Recognition of the fact that a tool's life may end either by a gradual build up of wear or by a catastrophic failure of the cutting edge such as chipping, fracture, etc., brought forth probabilistic models that contained a tool wear function as well as a hazard function. Recently, the tool wear phenomenon itself has been studied through probabilistic models that apply the concepts of single and multiple injury hazard functions. The probabilistic models and tool life distributions are listed in Appendix A, Table III. A more detailed discussion of some past work done with probabilistic models is given in Appendix B.

Stochastic and Dynamic Models

The stochastic nature of certain material removal phenomena such as grinding abrasive characterization, chatter and vibration, characterization of machined and ground surface topography, etc., was recognized during the early to mid-1960's. Models of this type were based on either discrete or parametric time series analysis through auto correlation functions or spectral analysis. Monte Carlo simulation techniques were also used. Stochastic and dynamic models for the development of the transfer functions for the machining processes such as grinding, turning, milling, etc., were introduced primarily for their potential use in adaptive control. During 1973, the use of continuous time series analysis was introduced for modeling, analysis and optimal control. This approach led to a differential equation for the process, the parameters of which were believed to have physical interpretation such as the natural frequency and damping factor. The major approaches and models that use stochastic and dynamic modeling techniques are listed in Appendix A, Table IV.

Models Other Than Tool Life

There have been a number of mathematical models for machining responses other than tool life, especially surface finish, cutting forces, horsepower, etc. These models have been primarily deterministic or statistical and are listed in Appendix A, Table V.

Conclusions

The following conclusions were drawn from the literature search:

(1) Most models have been developed on the basis of laboratory tests, primarily designed to illustrate the specific model building approach. The model building methodology that can be applied to production tool life has not yet been reported in the literature.

(2) Statistical inference techniques applicable to the use of tool life and other machining response models have not yet been fully developed.

(3) Although much of the theoretical ground work for mathematical models applicable to material removal processes has been laid, comprehensive experimental data and practical applications of the models are presently lacking.

In closing, it should be pointed out that the above models have been proposed mainly on the basis of limited experimental work done primarily in academic environments. Specific consideration should be given to the ability of a model to be relevant to an actual production environment.

2.3 Review of Statistical Experimental Design Methods Applied to Material Removal Processes

2.3.1 Introduction

The fundamental purpose of experimental design is to efficiently provide, through strategic interference with the system under study, a set of data which can be used to estimate the effects which process variables may have on process responses of interest. The specific nature of the experimental design is, of course, dependent upon the specific goals and objectives of the study at hand. Since mathematical model building is an iterative procedure by nature, these goals and objectives will be changing as information and knowledge is built up. In the early stages of an investigation when little is known about even which process variables may be important, two-level fractional factorial designs may be useful to provide the necessary information. In the latter stages of the model building procedure when the variables of importance are identified and even the appropriate model form is known, emphasis may shift to improving model precision and experiments may be designed through the D-optimal criterion.

While the design of experiments is highly subjective and requires sound judgment and common sense, several important considerations can be outlined which help to guide the design of the proper strategy. These are:

(1) When many variables are present and the unimportant ones are to be screened out, select the test points to emphasize the estimation of low order effects so as to keep the number of tests required within reason; two-level fractional factorials are useful here.

(2) When there is a suspicion of the presence of nuisance or extraneous factors or time trends which can cloud the desired results, select the test points and testing sequence to produce blocking of the nuisance factors. Designs such as the central composite design which can accommodate a sequence of orthogonal blocks of tests are commonly employed in these cases.

(3) When the appropriate model form has been determined, select the tests to maximize the improvement in model precision. The D-optimal criterion satisfies this goal.

(4) When several candidate models are being considered at one time, select the sequence of test points which place the model in greatest jeopardy and provide for the maximum model discrimination.

(5) When process optimization is desired and previous tests show that the optimum is being approached, select the tests to include sufficient levels of each variable to insure that the curvature of the response surface will be captured. Three level factorials and central composite designs are commonly used under these conditions.

(6) When little is known about the shape and orientation of the response surface relative to the independent variable space, select the test points in such a way to provide for uniform precision in the model predicted values over the region of the test points. Equal variance on circles or spheres emanating from the design origin is the product of employing the rotatibility criterion in the case.

In addition to the above general considerations and design criteria, several other factors surrounding the process under study should be taken into account and will impact the strategy developed. These include the general size and shape of the region of interest of the independent variables, the nature of the inherent

process error over the region of interest, the time and cost of experimental runs and the level of precision required for making predictions with the mathematical models developed from the data.

There are a number of critical factors which make mathematical modeling in material removal processes difficult. An enormous number of work materials and tool materials exist, each with widely varying and unique performance characteristics, making generalization and extrapolation difficult. Machine tools and materials are space and labor intensive. Experimentation is time consuming and expensive and often requires complicated setup and instrumentation to accurately and precisely measure performance. Unlike chemical and other batch processing industries, material removal processes deal with discrete parts manufacture for which the general environment is less easy to control, generally subject to high levels of inherent variation and less understood in terms of phenomenological characteristics or mechanism. In the infancy of material removal processes study, large numbers of time consuming and expensive experiments were performed to evaluate process performance. A lack of availability of appropriate experimental strategies and model building procedures severely hindered the work of the investigator. The statistical approach has contributed strongly in two fundamental ways. First, it has provided more powerful and yet more realistic ways to model and interpret metal processing phenomena in a more mathematically rigorous framework. Second, it has provided an approach capable of producing much more efficient and interpretable experimental procedures and data analysis. It is clear that such contributions should be welcome, given the inherent nature of metal cutting research.

2.3.2 Application of Experimental Design in Material Removal Processes

In 1964, Wu called attention to the power of the use of statistically designed experiments in metal cutting research and practice. The use of response surface methodology was demonstrated in the development of tool life models with the major points of emphasis being three-fold: (1) to provide an experimental strategy from which math models would be developed from very few strategically located tests; (2) to demonstrate the desireability of using more general model forms in

conjunction with statistical model checking procedures to produce the best model for the situation at hand (graduating polynomials were used in this study), and (3) to demonstrate the iterative nature of model building by providing a sequentially designed set of experiments. Since 1964, these concepts have become quite commonly employed in the development of math models in materials processing.

The use of two-level fractional factorials to identify important process variables was clearly illustrated by Wang, Taraman and Wu (1971) in the analysis of the punching process. The efficiency of such test schemes when several variables are under study, particularly when compared to a larger study by DeVries and Wu (1971) in which a complete two-level factorial was run to study eight variables in the drilling process is quite clear. In the punching study, the main effects of seven variables were estimated in only 16 tests with important insights with respect to two-factor variable interactions revealed as well. Wu and Meyer (1965) employed a one-half fraction of a 2^5 factorial to develop a first-order cutting tool temperature equation and in so doing, showed how a savings of 50% in the number of tests required over the full factorial could be achieved without loss of any relevant information.

Complete two-level factorials have been commonly used when the objective is to develop first order models or evaluate only main effects and two-factor interactions. Kuljanic (1973) employed a 2^4 design to study the milling process with particular emphasis on investigating the effect of machine stiffness on tool wear. Zakaria and El Gomayel (1975) studied the relationship bewteen cutting temperature and tool life using a 2^3 full factorial to vary speed, feed and depth of cut. Mukherjee and Basu (1973) developed first order models to predict tool life and surface finish in hot machining via a 2^4 factorial. A 2^5 factorial was used by Fujii, et al (1972) to evaluate the effects of drill grinding parameters and cutting conditions on torque and thrust in drilling. 2^3 factorials were the basis for a response surface methodology study of the inertia welding process. First order models were developed to determine the most favorable directions to proceed toward process optimization.

Higher order experimental designs are necessary when second order, third order or perhaps nonlinear models are to be developed. Lambert and Taraman (1973) employed the central composite design (CCD) configuration to develop second order polynomial models to predict cutting forces and surface finish. Williams and McGilchrist also used the CCD to develop the response surface of drill life as a function of drill geometry and cutting conditons. The 3-level factorial was used by Micheletti and Boer (1973) to develop a more comprehensive tool life equation and employ response surface methodology for optimization. In a study to compare tool life in single versus multi-tooth milling, four and five factors were employed to provide for a more comprehensive study of the variable effects for more settings of the independent variables. Two, three and five levels of the various factors were used by Zohdo (1974) to develop a factorial experiment to study the effects of grain size, coolant, depth of cut, table and cross feed on surface finish in grinding. A summary of the literature in this area is given in Appendix A, Table VI.

2.3.3 Illustrations of Standard Design Strategies Employed In Material Removal Processes

Various experimental designs are available to address the varied objectives in the area of machining experimentation and analysis. The following examples illustrate the most popular experimental designs that have been employed in metal removal processes and the objectives they accomplish.

Example 1: The initial investigation of a new process or procedure requires the "screening" of the process variables to determine those that are dominant. As an example, the introduction of a new tool material such as a ceramic or cubic boron nitride presents the possibility that process variables other than velocity and feed may have a significant effect on tool performance or that the effects may be totally different than those for HSS or carbide cutting. The list of such variables may include: radial depth of cut, axial depth of cut, side cutting edge angle, cutting fluid or coolant, nose radius, relief angle, various metallurgical treatments of the tool and others. The identification of the dominant variables should be done efficiently and simply with respect to designing tool life tests. The 2-level factorial and fractional factorial designs are used in this situation. Briefly, the design is constructed as follows:

1. Two reasonable levels are selected for each variable. These are designated high (+) and low (-) and represent the range of the variable under consideration.

2. For a full factorial all possible combinations of each level are run requiring 2^k tests (k = number of variables).

3. For a fractional factorial, a "fraction" of the full factorial is run.

The fractional factorial design is useful when k is large and the negligence of higher-order interactions between variables is assumed. Important points concerning the factorial design are:

1. The design is orthogonal. That is, independent estimates of the effect of each variable are obtained.

2. The design is simple to construct.

3. The effect of each variable is assumed linear and only first-order terms in a model can be estimated.

4. The design is efficient in terms of assessable parameters versus number of tests.

5. The design consists of a set number of tests.

The factorial-type design has become popular in many investigations of physical processes and its usefulness in early studies is well documented. It must be remembered, nevertheless, that in follow-up and more sophisticated investigations its usefulness becomes limited.

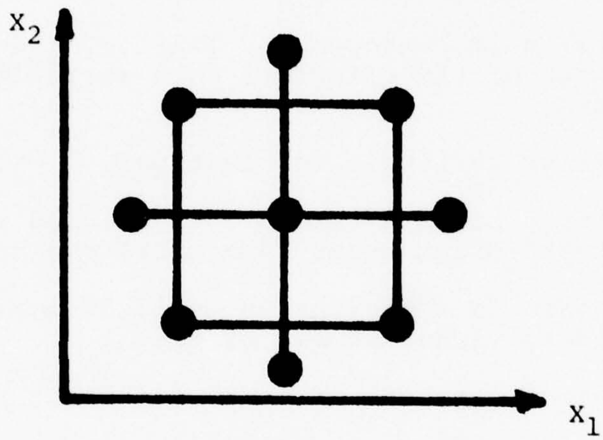
Example 2: The development of higher-order models for process responses which exhibit quadradic behavior. For example, in many tool life studies over a wide range of cutting conditions, the plotted tool life response in logarithmic coordinates is no longer linear. In this situation a second-order model is used and is commonly developed using standard stepwise regression packages which obtain the most appropriate model from a "Base Model" consisting of many terms including second-order terms and interaction terms. The experimental design used to obtain data to fit this model must have at least three levels of each variable. The central composite design (CCD) is often used. Briefly, the design is constructed as follows:

1. A full 2-level factorial design is set down (cube points).

2. Center point(s) are added at the center of the 2-level design.

3. Star points are added along lines projecting from the center point through the sides of the square or faces of the (hyper) cube at the appropriate distance from the center point.

An example in two variables would be,



Important points concerning the central composite design are:

1. Orthogonality can be easily obtained by selecting the correct distance of the "star" points from the center point and the number of replicated center points to be run.

2. Full second-order models are efficiently estimated.

3. The construction is easily accomplished.

4. The design can be made <u>rotatable</u>; that is, the uncertainty of predicted responses increase uniformly as the conditions where the predictions are made move away from the center of the design.

5. The design consists of a set number of tests.

6. The design can accommodate orthoganal blocking, ie, the tests can be run sequentially in two or more non-intersecting blocks of tests.

The central composite design finds its greatest use in the development of models to characterize the quadradic behavior of the response. Its use is limited in initial investigations or in highly constrained studies where the feasible experimental region is irregularly shaped and the placement of predefined designs, such as factorials and CCD is difficult.

Example 3: Process optimization via Response Surface Methodology. Investigations are often performed which seek out the operating levels of each controllable variable which optimizes the process response. In cases where prior knowledge of the optimal conditions is unavailable, an efficient and simple experimental search technique is Response Surface Methodology (RSM). Most physical examples are found in the chemical processing industry where the controllable variables such as temperature and pressure are continuous and easily controlled. The use in material removal processes has been limited, but possible applications could arise in the nontraditional material removal processes such as electrical discharge machining (EDM).

Response Surface Methodology is the merging of two techniques; factorial designs and second-order designs. The procedure is as follows:

1. Initially, run a full or fractional factorial design and estimate the linear effects of each variable in the region of the tests.

2. From the linear effects, compute the direction of steepest ascent (greatest improvement). This direction is the direction of largest slope along the response surface where the tests were run.

3. Run tests along the steepest ascent direction until no improvement in the response is achieved.

4. Set down another factorial-type design near the last test run and compute a new direction of steepest ascent.

5. Continue steps (3) and (4) until the improvement is small and the surface appears to be flattening out.

6. Set down a second-order design and compute a second-order model.

The model developed will permit an approximate description of the surface about the optimal as well as determining the optimal setting of the variables.

2.3.4 Needs and Directions in the Design of Material Removal Process Experiments

Since the early 1960's, the areas of planned experimentation in material removal process studies have advanced considerably. Today, two-level factorial and fractional factorial designs, three-level factorials, central composite design and the other organized statistically designed experiments are routinely used in material investigations where they were virtually unknown to the field fifteen years ago. The use of experimental procedures such as response modeling and process optimizing are also becoming more widely accepted.

With regard to experimental design for material removal processes, several directions need to be given more attention. A few of these areas of needed study and investigation are briefly outlined below.

1. Design of Experiments to Improve Model Precision and Predictive Capabilities:

   In the past, much attention was focused on the identification of important process variables and the determination of the appropriate model(s) to characterize a given situation. Factorials, fractional factorials and various second order designs have been useful in this regard. Today there is an emerging emphasis on mathematical modeling for prediction, control and optimization. Experimental design criteria and associated strategies should now place more emphasis on the predictive capabilities of the model.

2. Mathematical Modeling in Constrained Variable Spaces:

In early studies aimed at identifying important process variables, the nature of their effects and the development of descriptive math models, the design of machining experiments did not emphasize design economics as would be necessary in the design of experiments for process planning and economic production operations. As a result, little attention was explicity given to economic and operational constraints such as surface finish, metal removal rate, minimum and maximum tool life and tool forces and deflection. When such factors are used to define the economic region of study, the resulting variable space is generally reduced in size and irregularly shaped. Common symmetrically shaped designs are therefore difficult to accommodate and the necessary departures from symmetry result in a loss of the very properties that their regular shape was meant to provide. Design strategies based on economic criteria which can easily work within constrained variable spaces need to be pursued.

3. Development of Machining Data Bases on Shop Floor Production Operations:

The use of experimental design concepts to identify points of a process operation need not be confined to purely experimental (laboratory) process studies, e.g., variable identification, or process optimization. There is a strong need for individual users to develop their own data bases for process studies, scheduling, new process development, etc. To be powerful and of broad utility, a data base should be more than a collection of passively observed process results. It should contain data developed from pre-meditated process perturbations. Data bases collected across many users may be useful in terms of identifying starting points for process operations. However, individual users must operate their processes in such a way as to produce useful information on how to improve the process as well as the product itself.

4. The Complex Nature of Machining Data Variation:

Machining phenomena such as tool life are subject to high levels of variability of a somewhat complex nature. This variability is generally a function of the control variables and arises from several key sources including material variation, process stability, and the inhomogeneous nature of the cutting mechanics itself. The nature of process variation has important implications in the design of experiments and mathematical model fitting. Furthermore, the success of adaptive control which rests heavily with development of viable remote sensing will be influenced significantly by our understanding of process variability. Identification of explicit variation sources and improved process design and operation to control variation are important.

5. Development of Dynamic Data:

The impact of time series analysis on the study of material removal processes is now becoming significant. Temporal data collected on fundamental process responses has been shown to contain considerable information useable for process design, prediction and control. The design of experiments involving time series data is a new area which needs much study. Sampling methodologies for obtaining discrete records from continuous signals should be relevant here. Frequency response methods have in the past been used to identify the nature of system dynamics. New modeling concepts such as Dynamic Data Systems(DDS) are now being developed and applied to material removal processes.

It seems clear that mathematical modeling of material removal processes for design, prediction and control is a rapidly expanding area which will receive much attention in the next few years. Important ground has yet to be broken in the area of phenomenological models for metal cutting processes. An integral part of the development of this area is the development of methodologies for machining experimental design, both from laboratory and production floor points of view. Work must proceed on both of these points as the needs for fundamental research studies and improving present levels of machining productivity are met.

2.4 Experimental Design of Tool Life Experiments

2.4.1 Inherent Problems of the Tool Life Experimental Environment

The development of a tool life experimental strategy is complicated by the presence of certain salient inherent characteristics of tool life data and the general tool life experimental environment. These are the following:

1. The inadequacy of a theoretical understanding of the tool life phenomenon that has lead to a purely empirical approach in tool life investigation.

2. The highly non-symmetrical and irregularly shaped feasbile experimental region for metal cutting processes where tool life must be studied.

3. The complex nature of tool life data, particularly the behavior of tool life variation or scatter.

4. The high cost of tool life experimentation in terms of tools, material and time expended to develop an adequate tool life model within the economic operation region.

5. The uniqueness in individual machine tool/material/tooling combinations.

The existence of these characteristics brings great difficulty to the effective employment of commonly used experimental designs, such as factorials and composite designs.

The difficulty in understanding the precise failure mechanisms of cutting tools has caused many empirical model forms to be proposed to describe tool life behavior. Since 1907, Taylor's model which describes the observed exponential decrease in tool life as cutting speed is increased has been the most common model form. In recent years, complex and often nonlinear model forms have been proposed to account for the various inadequacies of the Taylor model. Most recent investigations employing reliability theory have led to probabilistic tool life model forms which may provide clues into the mechanisms of tool failure. These model forms need to be further investigated and experimental strategies developed which are capable of leading to new model forms, discriminating between available model forms or being used with various individual model forms.

Generally, production operations and experimental tool life investigations must be performed under various constraints. These constraints often limit the possible combinations of process variable levels and define a feasible experimental region. Various constraint equations (generally nonlinear) define the feasible experimental region of interest and vary for different cutting processes and part requirements. If the experimental region is to be confined to operating conditions conducive to economical machining, then commonly used symmetric experimental designs such as the 2- and 3-level factorial designs may not be appropriate since they cannot be easily adapted to or oriented within the irregularly shaped regions. The definition and construction of the feasible region for experimentation or production operation is a major aspect of any tool life experimental strategy.

The large levels and inherent behavior of tool life variation is a major concern in the development of tool life experimental strategies. Recent studies have shown that at wear levels commonly used in practice, the variation of tool life cannot be considered constant even within a relatively small experimental region. Certain cutting conditions within the operability region have smaller inherent variation, thereby giving more reliable information as to the true tool life response. Large material variation from composition, heat treatment and batch to batch (heat to heat) differences is a major source of the large scatter observed in the performance of cutting tools. The large scatter often requires many tests to describe the behavior of tool life, thereby necessitating efficient tool life experimental strategies. The high cost of tool life experimentation further requires efficient experimentation to perform only the needed objectives of model development with the minimum amount of testing.

The uniqueness of the tool life experimental situation with respect to individual machine tools, material and tooling suggests the difficulty of extrapolating results from an investigation into a production environment. It is hoped that the differences in the production environment are not so great that they would prevent the design of experimental strategies that would account for them. The experimental strategy would involve the construction of different feasible regions

for experimentation and production operation. The production experimental regions would be individually defined for the particular production situation. The experimental feasible region would include likely production regions and would be larger.

The tool life experimental environment is one in which the important factors which influence tool life have been identified and the forms of tool life models are known. The experimental strategy should concern itself more with the estimation of model parameters and the predictive capabilities of the model.

Two major aspects of the experimental strategy for tool life model development are (1) the proper construction of the feasible experimental region and (2) the selection and application of the experimental objective function or design criterion. That is, in what general region should the test be run and on what basis should the specific points be chosen? To these ends we will now discuss two interacting concepts explored in this project. The first is the development of probabilistic process constraints for economic region identification through sequential data development. The second is the use of the D-optimal experimental design criterion for the selection of test points within the identified region of interest.

2.4.2 Feasible Experimental Region Identification for Tool Life Model Development

In many production processes, constraints are often imposed on the operation and/or investigation of the process. These constraints are specified to satisfy part specifications, operational limitations and production or experimental economic requirements. For metal cutting tool life investigations, the constraints are particularly important. Part requirements such as surface finish and dimensional tolerances are commonly imposed on the production and, therefore, on the tool life investigation. Many constraints are imposed solely on the physical feasibility limits of operation for the process. For example, if the cutting speed for a turning process were very low, it may be impossible for the tool to cut the work material, i.e., to generate the necessary horsepower. Economic constraints on

production such as production rate and power consumption are imposed, as well as economic constraints for the investigation such as maximum number of tests, number of tools or amount of material to be tested, and overall time allowed for testing.

In addition to the necessity for many of these constraints, their implications to the investigation and operation of the process are important. These implications are:

1. Since the region of investigation in the variable space is specifically defined and located, it is generally smaller than many unconstrained investigations would use. Thus, the experimental model building procedure may employ simpler model forms and require fewer tests within the region. Often, only first order models are needed. This has the additional advantage of having fewer parameters to be estimated thereby further reducing the required number of tests.

2. The design of the tool life experiments is influenced by the constrained region of investigation. Standard experimental designs such as the 2-level factorial and other symmetric designs may not be as appropriate since it is difficult to orient them within the region. The more "continuous" and sequential nature designs, such as the D-optimal design, which defines an experimental objective function and then selects the tests within the region to optimize this objective function, would be better suited for constrained regions since they are naturally accommodated within a region of any size or shape.

3. The tool life investigation can be expanded to include the economic optimization of the process. Experimental objective functions may be defined which include the objective of searching out the region of investigation for the optimal operating conditions. In this sense, the investigation becomes a dynamic modeling and optimization procedure with possibilities of on-line, in production usage.

It should be clear that the definition of the various constraints and the construction of the feasible region of process investigation and production operation are critical aspects in the overall process optimization and control. The following sections present a general mathematical development of both probabilistic and deterministic contraints together with their application to machining studies. A machining example is provided.

Machining Constraints

Tool life investigations should be performed under conditions as close as possible to production conditions; therefore, the constraints imposed on the production process are also applied to the investigation procedure. As alluded to previously, the actual definition of constraints for laboratory investigations may be different from that for actual production. The production environment would be less tolerable of constraint violation than the laboratory environment since a production violation would likely cause unacceptable parts and production delays. A slight constraint violation in a laboratory investigation can be desirable since this may lead to a better understanding of the behavior of the constraint. The relationship between the feasible production region and the feasible experimental region is analogous to the statistical behavior of individual observations and mean observations. That is, the laboratory feasible region could be considered similar to the "confidence region" in which a high percentage of all individual production feasible regions would be contained within. For example, a laboratory region constructed by employing 95% probabilistic constraints should contain approximately 95% of all feasible production regions for the particular process under study. The different production regions would be the result of "micro" differences in the process, i.e., batch to batch differences, not "macro" differences such as a completely new material.

The analogy of individual observations versus mean observations with production feasible regions versus laboratory feasible regions leads us to develop two types of probabilistic constraints (see the following section on mathematical derivation of constraints). The first type, used for laboratory regions, is based

on the true mean constraint response, ($\hat{Y}_0$) which is similar to a confidence interval. The second type, used for production regions, would be based on individual future observations ($\bar{Y}_0$) which is similar to a prediction interval for one future observation. Probabilistic constraints will be referred to as "$\hat{Y}_0$-based" or "$\bar{Y}_0$-based" to signify the difference between constraints used for laboratory regions and production regions, respectively. As will be seen in the following sections, $\bar{Y}_0$-based probabilistic constraints yield smaller, more conservative feasible regions which is desirable for production operation.

The various constraints imposed on machining processes can be classified as deterministic, stochastic or probabilistic. The following constraints are commonly employed in production and/or laboratory situations:

A. <u>Metal Removal Rate:</u> It is necessary to define a minimum metal removal rate for a machining operation to ensure that some minimum production level is met. Below such a level, speeds and feeds will be far from any economic optimum production level. This constraint can be expressed as in.^{3} /min., pieces/hours. or min./piece. The constraint is expressed mathematically as,

$$g(V,f,d,...) \geq R_{MIN}$$

where the function g is the rate equation for the process.

<u>EXAMPLE: Turning</u>

$$R = 12Vfd$$

where R is the metal removal rate (in.^{3}/min.), V is the cutting velocity (ft./min.), f is the feed rate (in./rev.), and d is the depth of cut (in.). The constraint is deterministic and can be expressed mathematically as,

$$12Vfd \geq R_{MIN}$$

This relationship defines a subspace of the independent variables where the minimum metal removal rate constraint will be satisfied.

B. Machine Limits: The maximum and minimum settings for a particular process are specified. The maximum levels are defined by the machine limitation, or part specification, work-tool combination or operator safety limits. The minimum levels are set through economic directives or physical feasibility limits of operation, such as a cutting speed that is too slow will not generate the required horsepower to cut the material. These constraints are deterministic and are expressed as:

$$V_{MIN} \leq V \leq V_{MAX}$$

$$f_{MIN} \leq f \leq f_{MAX}$$

$$RD_{MIN} \leq RD \leq RD_{MAX}$$

C. Surface Finish/Cutting Force/Allowable Horsepower:

For general metal cutting processes, one or more of these three constraints are usually specified. For finishing operations, a limiting cutting force can be specified to insure dimensional accuracy; furthermore, surface finish requirements must often be satisfied. For roughing operations, the maximum power available for a machine must not be exceeded. Empirical models can be developed which describe the behavior of these constraints. In machining, it has been well established that the model form for all three constraints is the general power function,

$$f(V,f,d) = \alpha_o V^{\alpha_1} f^{\alpha_2} d^{\alpha_3} \qquad (1)$$

where the α's are the parameters of the model. Two options are available for obtaining numerical values of the α's.

i) Obtain parameter values from a handbook or a previous study involving the tool-work material combination, or

ii) Estimate the parameter values from data obtained during tool life experiments.

The first option provides a constraint model that is stochastic, i.e., an uncertain constraint phenomenon treated deterministically. The construction of this constraint would be similar to other deterministic constraints,

$$\alpha_0 V^{\alpha_1} f^{\alpha_2} d^{\alpha_3} \leq \begin{cases} \text{S.f. max.} \\ \text{F max.} \\ \text{HP max.} \end{cases} \tag{2}$$

The construction of probabilisitic constraints based on such information would not be possible unless a means of obtaining a variance estimate is available. The second option provides a more accurate model for the individual machining situation under study. Probabilisitic constraints should be developed. They will change as further tests are run and provide "dynamic" constraints which are sensitive to the individual machining environment. This would be particularly important in on-line production situations but not as important for laboratory experimentation. In the laboratory, conditions are more controlled and the range (distribution of operators, machines, materials, tools, cut, etc.) that may be experienced in production operations cannot be easily appreciated in the laboratory.

D. <u>Minimum and Maximum Tool Life Constraints:</u> It is desirable to run tool life tests so that the life of the tool is at least some minimum value but not exceeding some maximum value. These limits are set i) to insure that tests are run at conditions which would be economically feasible production conditions, and ii) to insure that irreparable tool damage (breakage or chipping) from very short tests and unduly prolonged testing from very long tests are avoided. Initially, a few unconstrained tests would have to be run to fit the tool life model and construct the probabilisitic tool life constraints. The same is true in constructing other probabilisitic constraints. As with the previously discussed constraints, a general power function of the form,

$$VT^{n_1} v^{n_2} d^{n_3} \varepsilon' = C \tag{3}$$

was used to characterize and predict tool life; where T denotes the random variable tool life, n_1, n_2, n_3 and C are parameters (to be estimated), and ε' is the random error (here assumed to be multiplicative). The logarithmic transformation conveniently linearizes this form; that is,

$$LnT = (1/n_1)LnC-(1/n_1)LnV-(n_2/n_1)Lnf-(n_3/n_1)Lnd+Ln\varepsilon'$$

which is the form of a first order linear model. The random error, ε, is assumed normally distributed with expected value zero and variance σ^2. For the tool life model development situation, it is common to assume that the standard deviation of observed tool life values is directly proportional to the observed mean tool life, i.e., $\hat{S}_T = k\bar{T}$, where k is the coefficient of variation (a constant), and $\hat{S}_T$ and $\bar{T}$ are estimated from replicated tests at a given set of cutting conditions. If the coefficient of variation is constant then the variance of log-transformed tool life values is constant, i.e., Var(LnT) = constant. Furthermore, it can be shown that the coefficient of variation is approximately equal to the standard deviation of the log-transformed tool life; $K \approx S_{Ln(T)}$.

This result allows us to use standard least squares regression analysis for the transformed tool life model since the assumption of constant variance ($VAR(\underline{\varepsilon} = \underline{I}\sigma^2)$ over the transformed variable space is satisfied. The construction of probabilisitic constraints follows directly from the regression analysis model. This construction will be presented in detail in the following section, but the constraint model obtained (based on $\hat{Y}_0$) is of the form;

$$EXP\left[\underline{x}\underline{\hat{b}} + t_{m,\alpha}\left[\underline{x}(\underline{X}^T\underline{X})^{-1}\ \underline{x}^T\right]^{1/2}\hat{\sigma}\right] \leq T_{max}\ \text{(maximum)} \tag{4}$$

$$EXP\left[\underline{x}\underline{\hat{b}} - t_{m,\alpha}\left[\underline{x}(\underline{X}^T\underline{X})^{-1}\ \underline{x}^T\right]^{1/2}\hat{\sigma}\right] \geq T_{min}\ \text{(minimum)} \tag{4a}$$

where $\underline{x\hat{b}}$ is the fitted tool life model (in matrix notation), $t_{m,\alpha}$ is the appropriate t-statistic, $\hat{\sigma}$ is the estimate of the inherent standard deviation, and $\underline{x}(\underline{X}^T\underline{X})^{-1}\ \underline{x}^T$ is the matrix representation of the variance of $\hat{Y}_0$ at $\underline{x}$.

Mathematical Derivation

Operational limitation or economic feasibility constraints are often an important element in the investigation and/or optimization of physical processes. Such constraints are classified as being either deterministic or stochastic and are generally expressed in the following form:

$$g(x) \leq U \text{ (maximum)} \tag{5}$$

$$g(x) \geq L \text{ (minimum)} \tag{5a}$$

where $\underline{x}$ is the vector of controllable variables, g is the function defining the constraint in the controllable variable space and U and L are the critical values for maximum and minimum constraints, respectively. The deterministic contraints are often defined through physical limitations, geometric relationships or operational directives. Stochastic constraints are often secondary process responses such as cutting forces, power consumption, surface finish, tool wear back, tool chipping and breakage, etc. The construction of the stochastic constraints is intended to take into consideration the uncertainty associated with obtaining the constraint model, i.e., the uncertainty of the constraint phenomenon itself. Such constraints are important, since strictly speaking, operations on exactly a stochastic constraint line will yield an expected constraint violation approximately half of the time. This concept becomes even more relevant since in many constrained optimization problems, the optimal solution lies on the constraint boundaries. While less conservative stochastic constraint function values may insure satisfactory process optimization, the proper values when treated probabilistically provide for a more realistic process environment and allow the extremes to be approached in a more controlled manner. It is therefore appropriate to express constraints probabilistically as:

$$Pr \left\{ g(\underline{x}) \leq U \right\} \geq 1-\alpha \text{ (maximum)} \tag{6}$$

$$Pr \left\{ g(\underline{x}) \geq L \right\} \geq 1-\alpha \text{ (minimum)} \tag{6a}$$

where α is the risk of violating the constraint. For deterministic constraints, the value of α is zero and the function g ($\underline{x}$) is simply the equation derived for the constraint in terms of the controllable variables.

For stochastic constraints, the function g(x) is constructed using the empirically developed constraint model and its underlying distributional properties. Constraint models commonly used are of the linear form

$$\underline{Y} = \underline{Xb} + \varepsilon$$

where

$\underline{Y} = (y_1, y_2, \ldots y_N)^T$ is the (N x 1) vector of observed responses.

$\underline{X} = (\underline{x_1}^T \underline{x_2}^T \ldots \underline{x_N}^T)^T$ is the (N x P) matrix of independent variables where $\underline{x_i}$ is the (1 x p) vector of controllable variables for the i^{th} test.

$\underline{\varepsilon} = (\varepsilon_1, \varepsilon_2, \ldots \varepsilon_N)^T$ is the error matrix assumed to be NID $(0, \underline{I}\sigma^2)$*

$\underline{b} = (b_1, b_2, \ldots b_p)^T$ is the (p x 1) vector of model parameters.

The least squares estimates of the parameters $\underline{b}$ are given by

$$\hat{\underline{b}} = (\underline{X}^T\underline{X})^{-1} \underline{X}^T\underline{Y} \tag{7}$$

and

$$\mathrm{Var}(\hat{\underline{b}}) = (\underline{X}^T\underline{X})^{-1}\hat{\sigma}^2 \tag{8}$$

$$\mathrm{Var}(\hat{Y}_0) = \underline{x}_o^T(\underline{X^TX})^{-1} \underline{x}_o \hat{\sigma}^2 \tag{9}$$

$$\mathrm{Var}(\hat{Y}_0) = \mathrm{Var}(\hat{Y}_0) + \hat{\sigma}^2/g \tag{10}$$

*When the assumption of homogeneous variance is not justified, the weighted least squares always is performed as described in Appendix C.

where $\hat{Y}_0 = \underline{x}_0\underline{b}$ is the predicted true mean response at $\underline{x}_0$, and $\bar{Y}_0$ is the predicted individual future observation.

To construct the $g(\underline{x})$ function for probabilistic constraints, the distribution for $\hat{y}_0$, the predicted true mean constraint response and $\bar{y}_0$, the predicted response for a single future observation is used. Both variables are assumed to be normally distributed with expected value equal to $\underline{x}_0\hat{\underline{b}}$ and variance given by equations (9) and (10), respectively. The construction of $g(\underline{x})$ takes the form of a one-sided test of hypotheses with the test's critical value equal to the critical constraint value. The function $g(\underline{x})$ is then defined as the locus of points in the controllable variable space which satisfies the requirement that the critical value in the appropriate (minimum or maximum) one-sided test of hypotheses is the critical constraint value. For probabilistic constraints based on $\hat{Y}_0$ (used for laboratory investigations) the function $g(\underline{x})$ is defined as,

$$g(\underline{x}) = \hat{Y}_0 - t_{m,\alpha}(\text{Var }(\hat{Y}_0))^{\frac{1}{2}} \quad \text{(minimum)} \qquad (11)$$

$$\hat{Y}_0 + t_{m,\alpha}(\text{Var }(\hat{Y}_0))^{\frac{1}{2}} \quad \text{(maximum)} \qquad (11a)$$

where $t_{m,\alpha}$ is the t-statistic for m degrees of freedom. For probabilistic constraints based on $\bar{Y}_0$ (used in production operation) the function $g(\underline{x})$ is defined as,

$$g(\underline{x}) = \bar{Y}_0 - t_{m,\alpha}(\text{Var }(\bar{Y}_0))^{\frac{1}{2}} \text{ (minimum)} \qquad (12)$$

$$\bar{Y}_0 + t_{m,\alpha}(\text{Var }(\bar{Y}_0))^{\frac{1}{2}} \text{ (maximum)} \qquad (12a)$$

Therefore, for linear constraint models of the form $\hat{\underline{Y}} = \underline{x}\hat{\underline{b}}$, the $(100-\alpha)\%$ constraints which satisfy

$$\Pr\left\{g_1(\underline{x}) \geq L\right\} \geq (100-\alpha)\% \quad \text{(minimum)}$$

and

$$\Pr\left\{g_2(\underline{x}) \leq U\right\} \geq (100-\alpha)\% \quad \text{(maximum)}$$

are given as

$$g_1(\underline{x}) = \underline{x}\hat{\underline{b}} - t_{m,\alpha}(\underline{xQx}^T \hat{\sigma}^2)^{\frac{1}{2}} \qquad (13)$$

and

$$g_2(\underline{x}) = \underline{x}\hat{\underline{b}} + t_{m,\alpha}(\underline{xQx}^T \hat{\sigma}^2)^{\frac{1}{2}} \qquad (13a)$$

for constraints based on the predicted true mean ($\hat{Y}_0$); or

$$g_1(\underline{x}) = \underline{x}\underline{\hat{b}} - t_{m,\alpha}\left[\left[\underline{xQx}^T + 1\right]\hat{\sigma}^2\right]^{1/2} \quad (14)$$

$$g_2(\underline{x}) = \underline{x}\underline{\hat{b}} + t_{m,\alpha}\left[\left[\underline{xQx}^T + 1\right]\hat{\sigma}^2\right]^{1/2} \quad (14a)$$

for constraints based on the individual future observations, where $\underline{Q} = (\underline{X}^T\underline{X})^{-1}$. The surfaces $g_1(\underline{x}) = L$ and $g_2(\underline{x}) = U$ define the constraint boundaries for the feasible space.

Probabilistic Constraint Example

A simulated tool life study for the end milling process was performed to illustrate the nature and behavior of probabilistic constraints under various conditions. A single constraint, minimum tool life of 15 minutes, was used to illustrate the following characteristics of probabilistic constraints: first, the general difference between non-probabilistic (stochastic) and probabilistic constraints; second, the difference between $\hat{Y}_0$-based (laboratory) and $\bar{Y}_0$-based (production) probabilistic constraints; third, the behavior of probabilistic constraints as the risk level (α) is changed; and fourth, the behavior of probabilistic constraints as the degrees of freedom (m) are increased. These four characteristics were studied using identical tool life results provided by an end milling tool life simulator. The construction of the simulator is discussed in Section 2.5.2.

The tests used were part of a larger investigation performed to evaluate various complete tool life experimental strategies as described in Section 2.5.3. The end milling study used three controllable variables; cutting speed, feed rate, and radial depth of cut. Eight tool life tests, defined by a 2^3-factorial and given in Table III were simulated, and the results were used to fit the following tool life model,

$$\text{LnT} = 10.71 - 2.28\text{LnV} - .53\text{Lnf} - .78\text{LnRD} \quad (15)$$

or in matrix notation,

$$\text{LnT} = \underline{x}_o\underline{\hat{b}} = (1 \ \text{LnV} \ \text{Lnf} \ \text{LnRD})\ (10.71\ -2.28\ -.53\ -.78)^T \quad (15a)$$

with $\hat{\sigma}^2 = .0625$ (residual mean square).

Using this fitted model, the probabilistic minimum tool life constraint is expressed as

$$\Pr\left\{ g(\underline{x}_o) \geq 15 \right\} \geq (100-\alpha)\% \tag{16}$$

where, for $\hat{Y}_0$-based constraints,

$$g(\underline{x}_o) = \underline{x}_o\underline{\hat{b}} - t_{m,\alpha}(\underline{x}_o\underline{Q}\underline{x}_o^T\,\hat{\sigma}^2)^{\frac{1}{2}} \tag{17}$$

and for $\bar{Y}_0$-based constraints,

$$g(\underline{x}_o) = \underline{x}_o\underline{b} - t_{m,\alpha}((\underline{x}_o\underline{Q}\underline{x}_o^T + 1)\,\hat{\sigma}^2)^{\frac{1}{2}} \tag{18}$$

The matrix $\underline{Q}$ is defined by the design matrix, $\underline{X}$, and is given as

$$\underline{Q} = (\underline{X}^T\underline{X})^{-1} \tag{19}$$

where

$$\underline{X} = \begin{bmatrix} 1 & LnV_1 & Lnf_1 & LnRD_1 \\ 1 & LnV_2 & Lnf_2 & LnRD_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & LnV_8 & Lnf_8 & LnRD_8 \end{bmatrix} \tag{20}$$

and where, V_i, f_i, and RD_i are the test conditions for the i^{th} test. The various probabilistic constraints were constructed with identical values for $\underline{Q}$, $\underline{\hat{b}}$, and $\hat{\sigma}^2$. The figures used were constructed in the speed-feed plane for a constant radial depth of cut (RD = .3 in.).

Figure 4 shows contours of constant expected tool life ($T = \underline{x}_o\underline{\hat{b}}$) for the fitted model. With the non-probabilistic minimum allowable tool life constraint of 15 min. the feasible region would be to the left and below the 15 min. contour. In general, probabilistic constraints are more conservative than non-probabilistic constraints. Probabilistic constraint boundaries will define points whose expected response is well above the minimum allowable level and below the maximum level. The margin of safety is designed to insure a higher probability that the constraint will not be violated. This shift in the constraint boundary is the most evident effect of employing probabilistic constraints as illustrated in detail in the following figures.

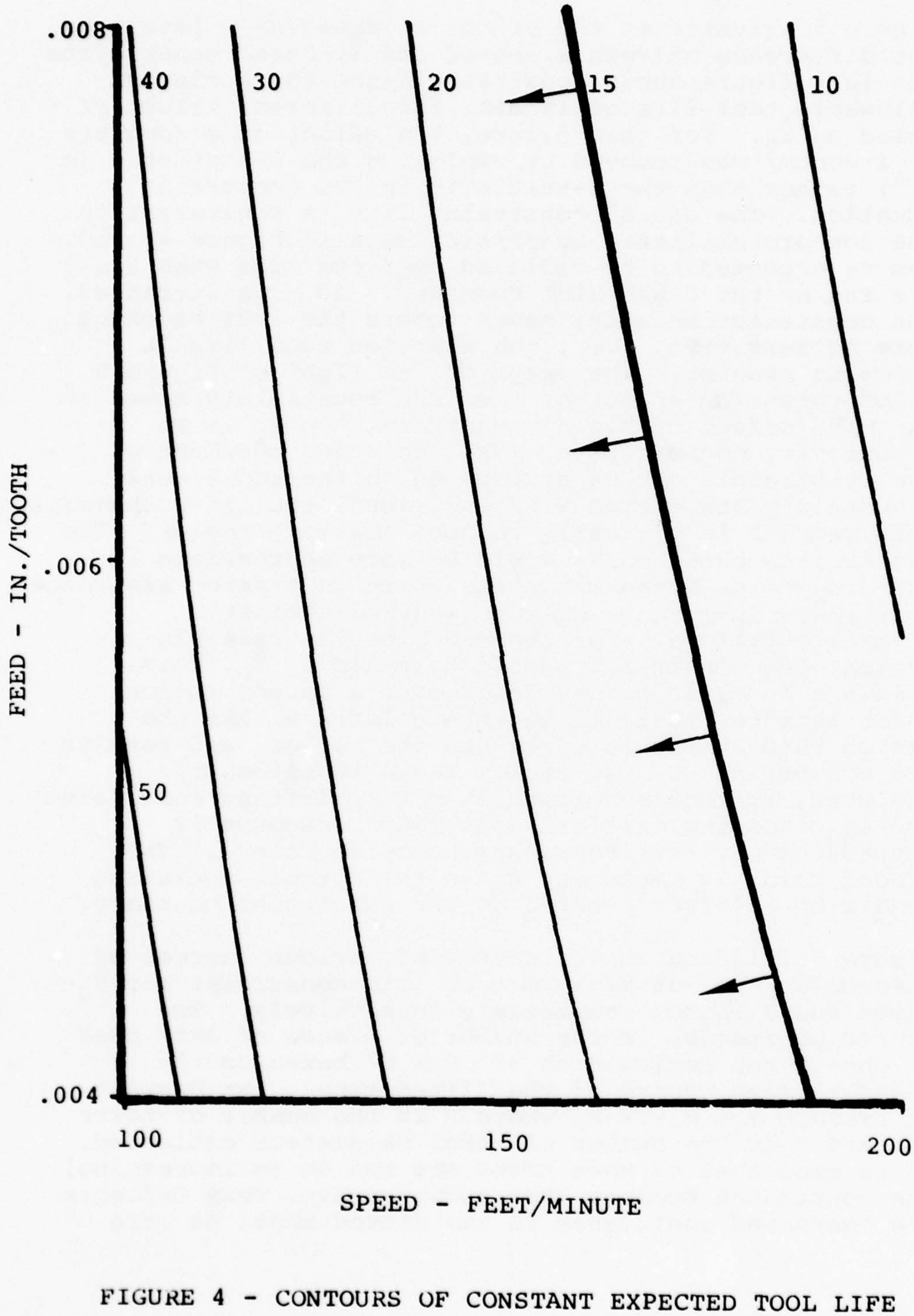


FIGURE 4 - CONTOURS OF CONSTANT EXPECTED TOOL LIFE

Figure 5 illustrates the effect of changing α level and the difference between $\hat{Y}_0$-based and $\bar{Y}_0$-based constraints. The left figure shows constraint lines for a minimum allowable tool life of 15 min. for different values of α based on $\hat{Y}_0$. For this figure, the effect of m (degrees of freedom) was removed by employing the Z-statistic ($m = \infty$) rather than the t-statistic in the constraint equation. The $\alpha = .50$ constraint line is equivalent to the non-probabilistic constraint seen in Figure 4, and can be expected to be violated half the time when tests are run at the constraint boundary. As α is increased, the constraint boundary moves toward the left becoming more conservative, i.e., the expected tool life is becoming greater. The graph on the right of Figure 5 illustrates the effect of α on the constraints based on $\bar{Y}_0$. The effect of basing constraints on $\bar{Y}_0$ is to become very conservative. The increased movement of the constraints can be attributed to the additional uncertainty associated with individual tool life observations. This results in a greatly reduced feasible region. The constraints based on $\bar{Y}_0$ would be more appropriate in the production operation since there is greater assurance that individual tools will be guarded against premature failure. For the experimental feasible region, the constraint should be based on $\hat{Y}_0$. This allows a model to be developed over a larger region which is more likely to be interpolated within the region than extrapolated beyond the region, and permits the constraints of the region to be occasionally violated, thereby resulting in better fitting constraint models since the critical constraint response is "straddled" by test responses below and above. This second point is important since the optimal operating condition is often located on the constraint boundary.

Figure 6 illustrates the effect of various degrees of freedom on the 95% minimum tool life constraint for $\hat{Y}_0$-based and $\bar{Y}_0$-based constraints respectively. The degree of freedom is the number of pieces of data used to obtain the estimate of σ^2. For $\hat{\sigma}^2$ based on the residual mean square of the fitted model, the degrees of freedom are m = N-P, where N is the number of tests run and P is the number of model parameters estimated. It is seen that as more tests are run (m is increasing) the constraint becomes less conservative. This reflects the increased confidence in the fitted model as more

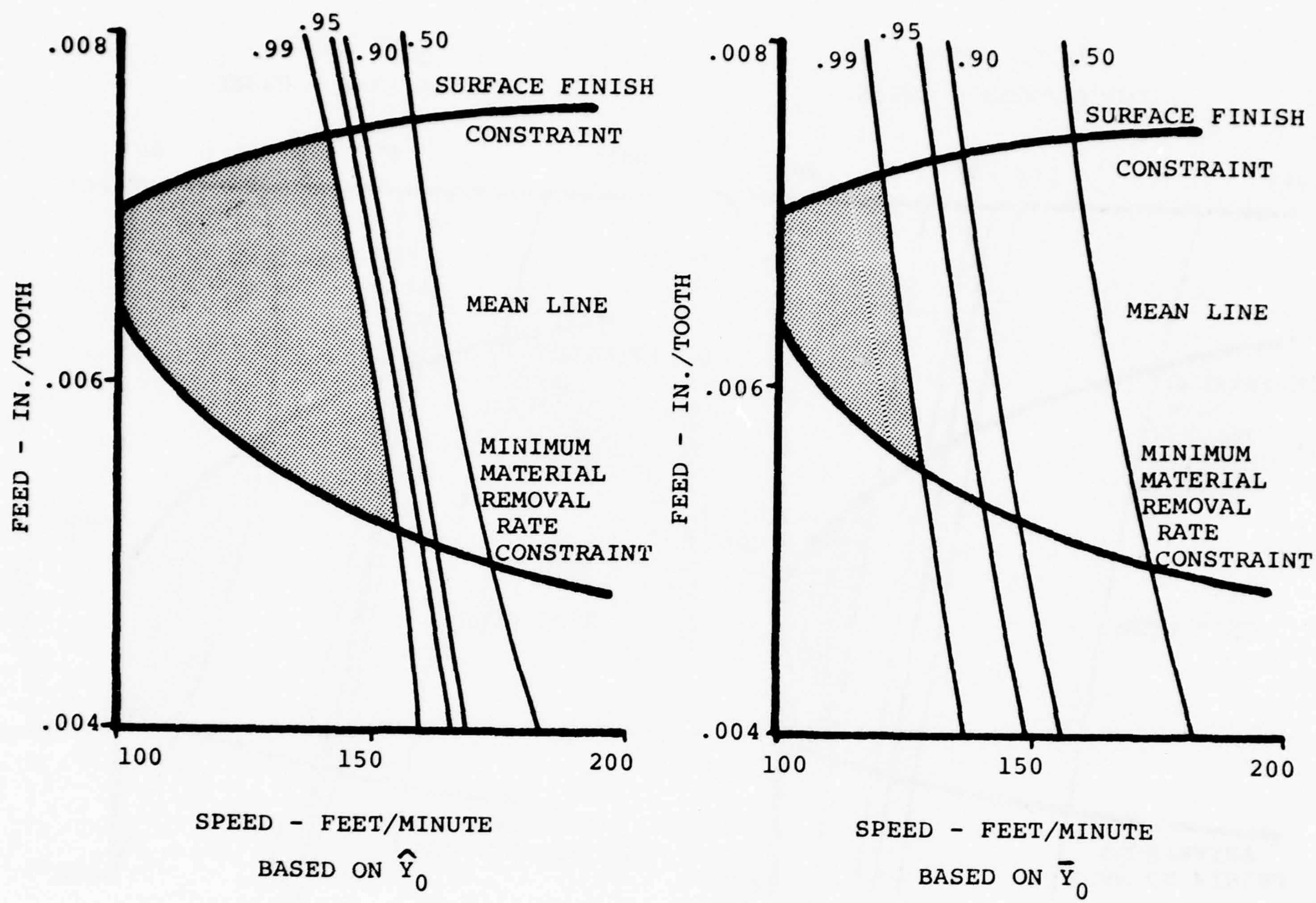


Figure 5 - MINIMUM PROBABILISTIC TOOL LIFE CONSTRAINTS FOR VARIOUS VALUES OF α FOR RADIAL DEPTH = 0.3 AND TIME = 15 MINUTES

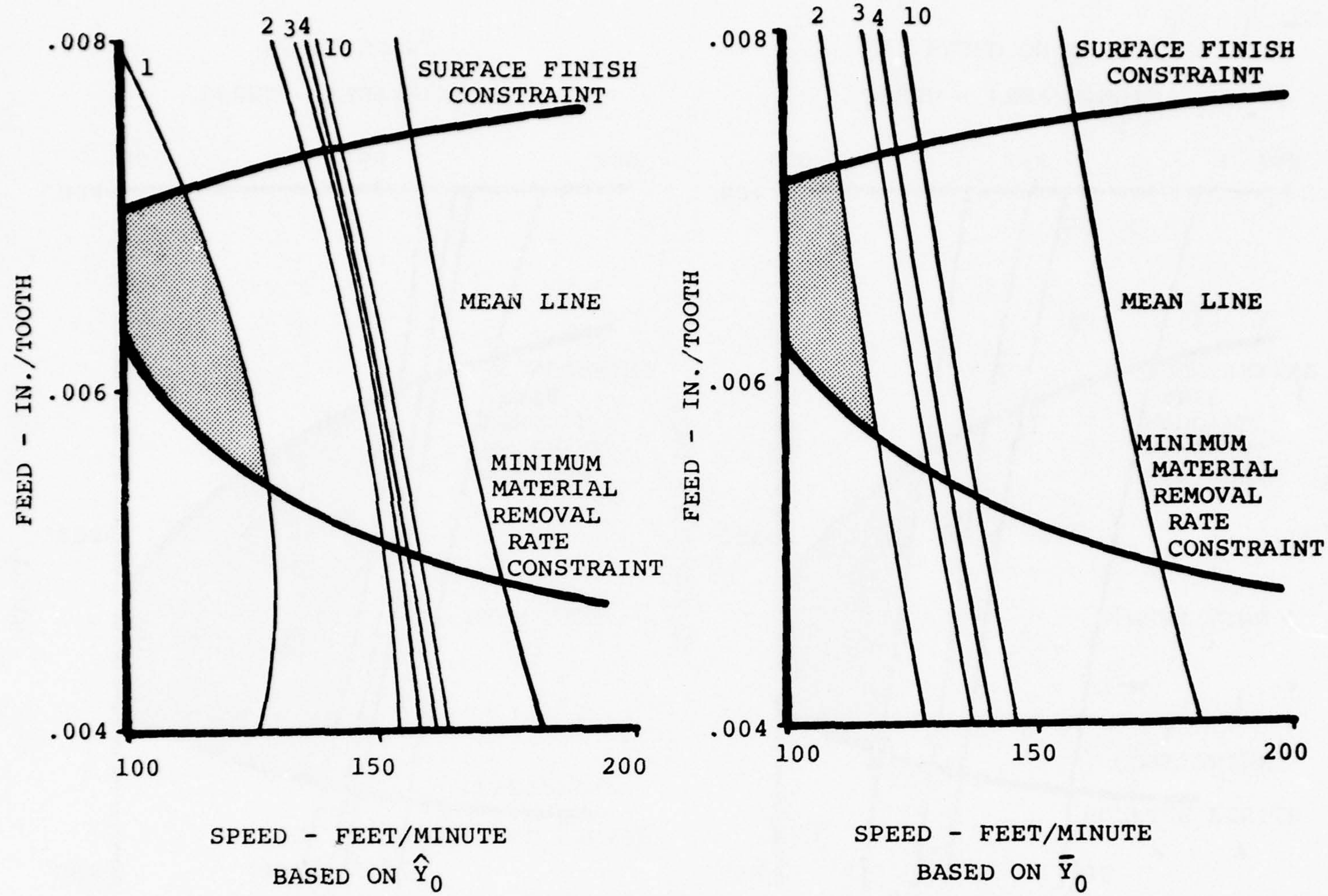


Figure 6 - MINIMUM PROBABILISTIC TOOL LIFE CONSTRAINTS FOR VARIOUS DEGREES OF FREEDOM FOR REDIAL DEPTH = 0.3 IN., TIME = 15 MINUTES, AND $\alpha = 0.05$

information is obtained. Figure 6 shows that a sizable change in the constraint occurs in going from $m = 1$ to $m = 2$.

This change dramatically increases the feasible experimental region, and suggests that the number of initial tests run be at least two more than the number of parameters in the model. When developing tool life experimental strategies, a major aspect is the selection of the number and location of the initial set of tests. The effect of degrees of freedom on the probabilistic constraints provides some guidelines in this area.

Two additional points concerning the behavior of probabilistic constraints should be mentioned that were not readily apparent from the previous figures. First, the shape of the constraint is highly dependent on the previous test placement (the $\underline{X}$ matrix). As the constraint is extrapolated beyond the current test region, it becomes very conservative as a result of the increasing variance of predicted values away from the test region. Second, the constraint is dynamic in the sense that it changes as tests are run and the model is refit. These two points will be brought out in Section 2.5.2 when a complete sequence of tool life tests are simulated.

The following conclusions concerning the behavior of probabilistic constraints can be made.

1) Probabilistic constraints produce smaller feasible regions of interest than non-probabilistic constraints, i.e., they are more conservative. Both laboratory and production machining tests will benefit from a reduction in the occurrence of uninformative and/or costly unsuccessful tests.

2) Constraints based on $\bar{Y}_0$ are more conservative than those based on $\hat{Y}_0$ and are appropriate in production situations since they greatly reduce the opportunity for "test" results which are not consistent with production requirements.

3) As the risk level (α) or the degrees of freedom (m) is increased the constraints become less conservative, i.e., the feasible region of interest becomes larger.

4) The constraints should be thought of as dynamic in the sense that they are continually updated and the region redefined as future tests are run.

2.4.3 D-Optimal Design Criterion

Introduction

In formulating a tool life experiment strategy, it must be realized that the experimental objectives vary with the particular situation at hand and, therefore, require approaches with differing points of view. For the general modeling situation, any one or more of several objectives could be of interest. These might be important variable identification, blocking out nuisance environmental factors, achieving discrimination among several candidate models, response surface identification for optimization and control, precise parameter estimation, and improved model predictive capabilities which take into account the inherent nature of the variation over the design region. The tool life experimental situation is one in which the important factors which influence tool life have been identified and the forms of tool life models are known. The experimental design strategy should concern itself more with the estimation of the model parameters and the predictive capabilities of the model.

The D-optimal criterion has a long history dating back to Smith in 1918 and has many appealing properties. Box and Lucas showed that D-optimal experimental designs lead to confidence regions of the smallest (hyper) volume in the parameter space. Kiefer showed that these designs minimize the maximum variance of any predicted value over the experimental space. Further attractive properties of the criterion are that it minimizes the general variance of the parameter estimates and that the design generated is invariant to parameter scale changes. However, the condition for the optimal advantage to be gained is that the correct model is known. Since the criterion is model dependent, it is generally used in situations where the phenomenon under study is somewhat well known in terms of important variables and appropriate model forms.

There are numerous advantages to employing the D-optimal criterion which have particular appeal to the tool life situation; they are:

(1) It forces the experimentor to give some thought to the model form before actual experimentation.

(2) The number of experiments is not restricted in any manner (to be a power of 2, for example)

(3) Sequential experimentation is easily handled in the linear and nonlinear situations.

(4) Precision in the model predictions can be enhanced with a minimum of experimentation.

(5) Nonsymmetrical design regions are easily examined since the D-optimal criterion does not, in general, define the test points a priori. This gives the ability to "custom fit" a design to a particular design region and model form.

(6) The inhomogeneous variance situation can be easily handled with the D-optimal criterion.

It is clear that these advantages match well with many of the problems inherent in the tool life modeling situation.

<u>Mathematical Statement of Criterion</u>

The D-optimal criterion may be summarized as follows:

Consider the (in general, nonlinear) model,

$$Y_i = f(\underline{x}_i, \underline{\beta}) + \varepsilon_i \tag{21}$$

where $\underline{\beta} = (\beta_1, \beta_2, \ldots, \beta_p)$ is a vector of p parameters to be estimated; $\underline{x}_i = (x_{1i}, x_{2i}, \ldots x_{iq})$ is a vector of q variables whose settings determine the i^{th} experimental test conditions; ε_i is the error for the i^{th} test, assumed to be normally and independently distributed with mean zero and constant variance.

The matrix $\underline{X}$ is then defined to be:

$$X = \begin{bmatrix} \delta f(x_1, \beta)/\delta\beta_1 & \delta f(x_1/\beta)/\delta\beta_2 \ldots \delta f(x_1, \beta)/\delta\beta_p \\ \delta f(x_i, \beta)/\delta\beta_1 & \delta f(x_i/\beta)/\delta\beta_2 \ldots \delta f(x_i, \beta)/\delta\beta_p \\ \delta f(x_N + K, \beta)/\delta\beta_1 & \delta f(x_N + K, \beta)/\delta\beta_2 \ldots \quad \delta f(x_N + K, \beta)/\delta\beta_p \end{bmatrix} \tag{22}$$

where the first N rows correspond to the experiments already run, and the last k rows correspond to the next k tests to be run. To provide the above stated properties, the D-optimal criterion is to maximize the determinant of the $\underline{X}^T\underline{X}$ (cross-product) matrix. It is common to let k equal 1 and sequentially plan the tests by employing information received from the last test (and all previous tests) to decide upon the next test condition.

For the special case where the model is linear in the parameters (such as the log transformed Taylor tool life model), it is possible to optimally design the complete set of experiments in advance. This is true since for models linear in the parameters, the partial derivatives in Eq. (22) are functions of the test conditons alone. Complete D-optimal experimental designs have been computed for standard linear models employed in rectangular regions. Many of these D-optimal designs are exactly equal, or are very close, to the commonly used symmetric designs. These symmetric designs not only possess other desirable properties such as simplicity, rotatability, and orthogonality, but are also optimal or very near optimal as defined by the D-optimal criterion for the particular linear models.

D-Optimal Examples in Tool Life Modeling

The following examples illustrate the various properties of the D-optimal design criterion.

I. Model Dependency of D-Optimal Designs

The model dependency of D-optimally designed tests is illustrated by comparing the resultant designs for the following models:

The linearized Taylor model with the interaction term added

$$E(\ln(T)) = B_0 + B_1x_1 + B_2x_2 + B_{12}x_1x_2 \tag{23}$$

and the second-order equation employed by Wu

$$E(\ln(T)) = B_0 + B_1x_1 + B_2x_2 + B_{12}x_1x_2 + B_{11}x_1x_1 + b_{22}x_2x_2 \tag{24}$$

where $x_1 = \ln(V)$, $x_2 = \ln(f)$

For the four-parameter linear model (Eq. 23), the D-optimal design is easily proved mathematically to be the two-level factorial design which fills a rectangular operability region. For the second order model (Eq. 24), the D-optimal design is closely approximated by a full three-level factorial design.

II. Precision Improvement of D-Optimal Designs

To illustrate the precision improvement obtained in the fitted tool life models when D-optimal designs are used, a comparison was made with results obtained from a Central Composite Design. Figures 7a and 7b show variance contours for $\ln(\hat{T})$ when the four-parameter linear model is used and fitted with the 2-level factorial (D-optimal) design and the CCD, respectively. Comparing the variance contours from the D-optimal design after eight tests with the variance contours from the CCD after nine tests, it appears that the center of the design region has approximately equal variance levels but differs near the design boundaries. Figures 7c and 7d show the variance contours for the second-order model after nine tests for both the 3-level factorial D-optimal design and the CCD, respectively. The maximum variance for both models appears to be at the extremes of the region. Table I lists the required number of tool life tests for both models using both the appropriate D-optimal design and the CCD to obtain a $\pm$ 20 percent level of precision in any predicted tool life value within the operability region.

III. Adaptability of D-Optimal Designs to Irregularly Shaped Feasible Experimental Regions

The nonlinear model suggested by Konig and DePiereau (1969)

$$E(\ln(T) = B_0 + b_1 V^{B_2} + B_3 f^{B_4} \tag{25}$$

was used to illustrate the D-optimal designs ability to adapt to irregularly shaped operability regions. D-optimal designs were calculated for two cases:

Case I: For a rectangular design region;

Case II: For a nonsymmetrical design region constrained by the operational limitations of maximum allowable horsepower, minimum metal removal rate and maximum allowable surface finish.

The D-optimal points selected for Case I are shown in Figure 8a. While the tests appear not to follow any symmetric or regular pattern, some general observations can be made; namely, (1) Most points (32 out of 36) fall on the boundaries of the operability region. This is expected since the variance of predicted tool life

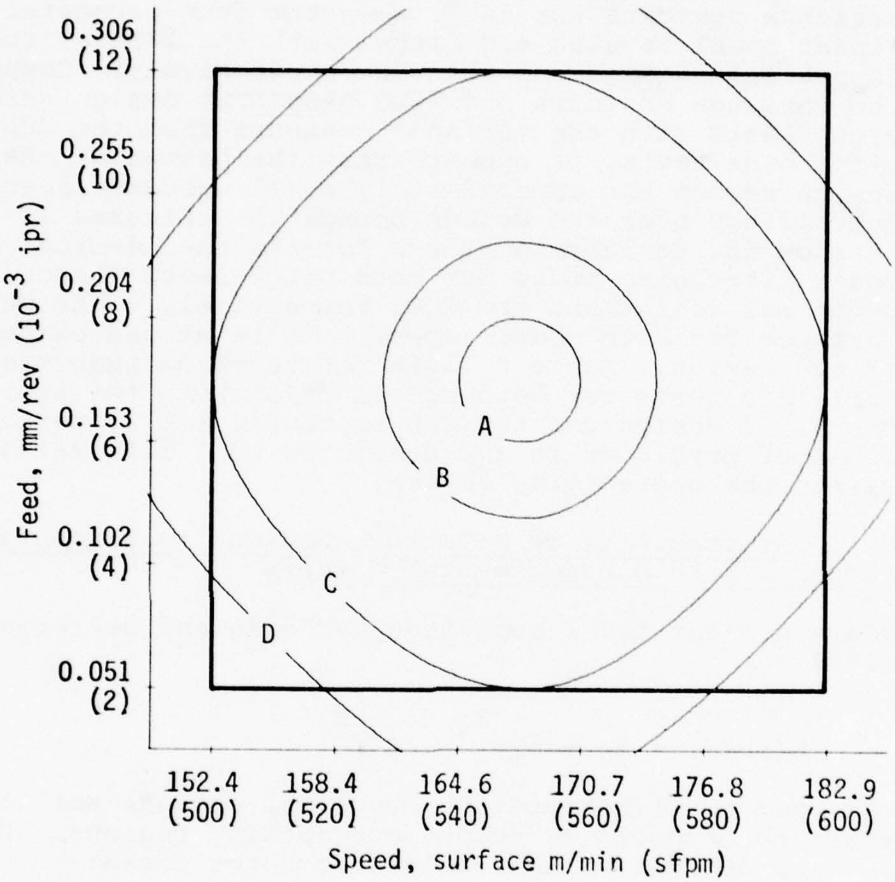


FIGURE 7a - CONTOURS OF CONSTANT VARIANCE OF PREDICTED LnT FOR TAYLOR'S LINEARIZED MODEL AFTER 8 D-OPTIMAL TESTS; LEVEL CODES: A = 0.13, B = 0.15, C = 0.25, D = 0.35

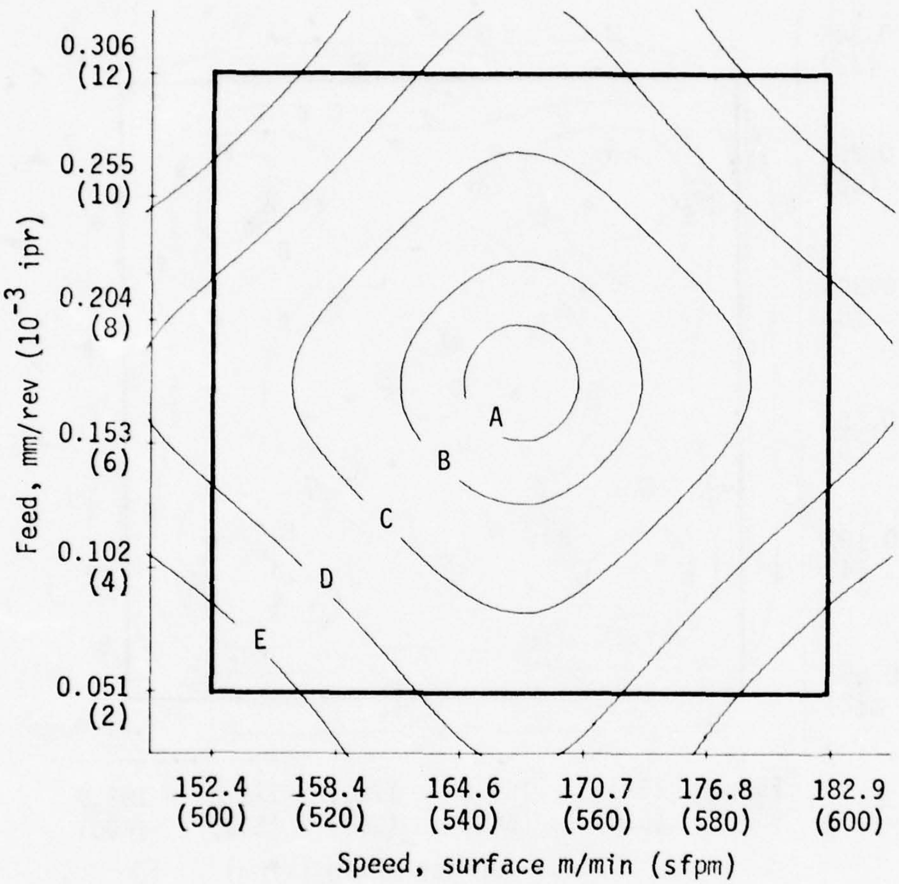


FIGURE 7b - CONTOURS OF CONSTANT VARIANCE OF PREDICTED LnT FOR TAYLOR'S LINEARIZED MODEL AFTER 9 TESTS BASED ON A CCD; LEVEL CODES: A = 0.12, B = 0.15, C = 0.25, D = 0.50, E = 1.0

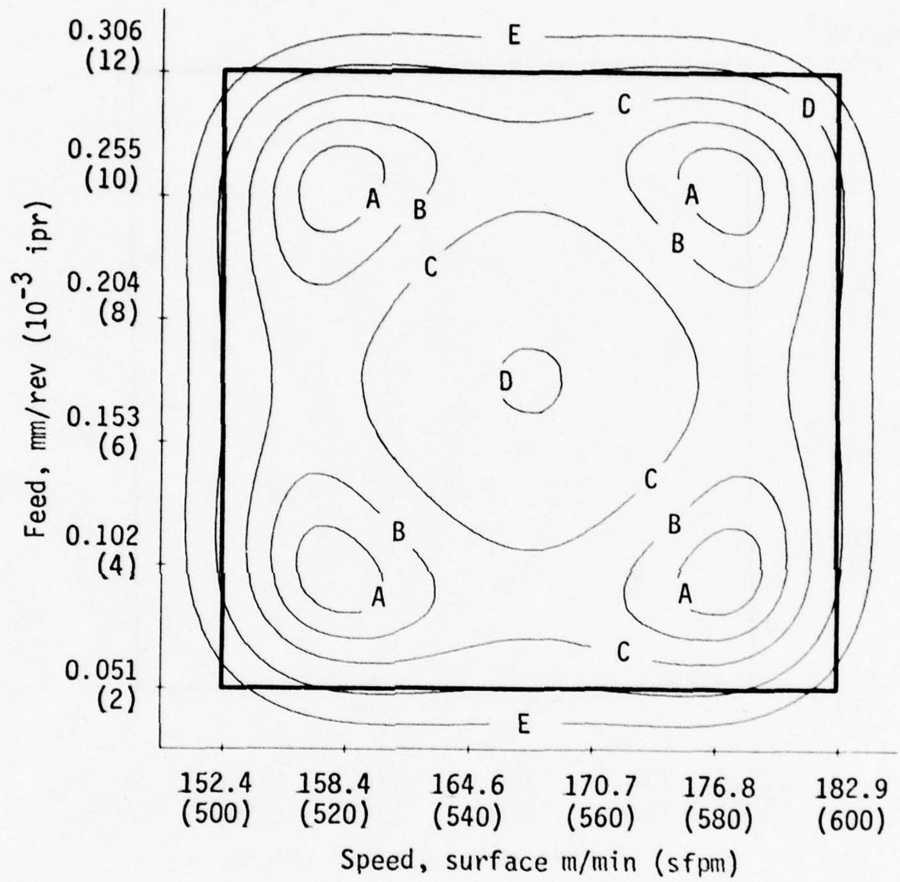


FIGURE 7c - CONTOURS OF CONSTANT VARIANCE OF PREDICTED LnT FOR Wu's SECOND-ORDER MODEL AFTER 9 D-OPTIMAL TESTS; LEVEL CODES: A = 0.37, B = 0.40, C = 0.45, D = 0.55, E = 0.70

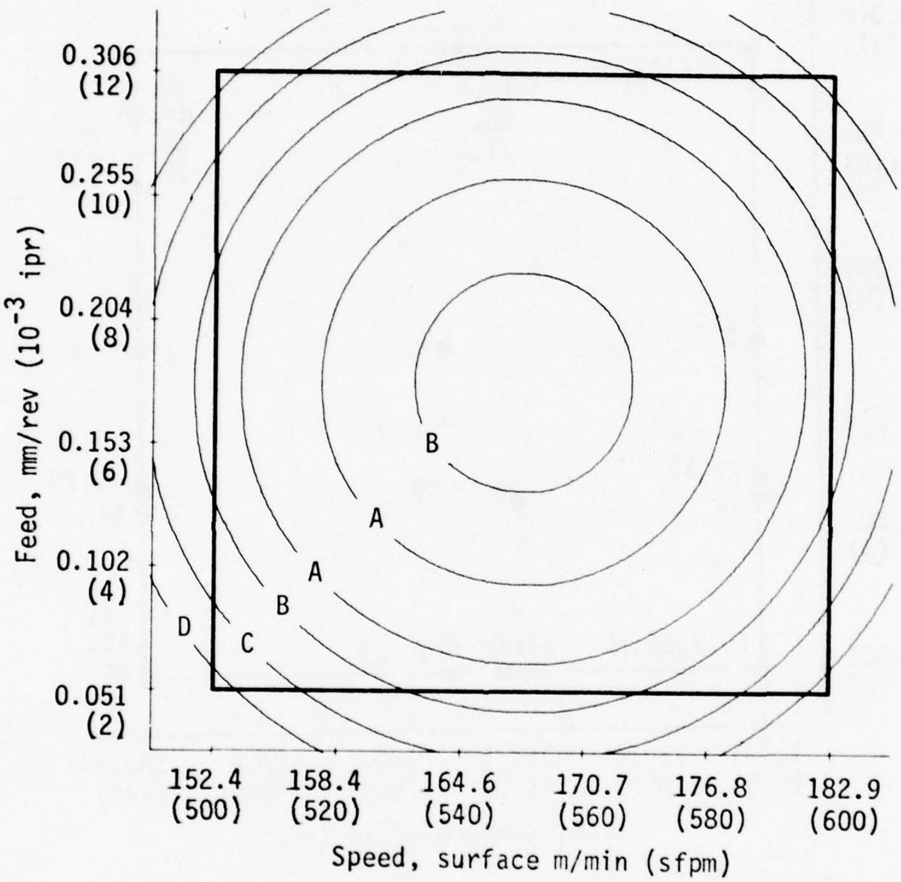
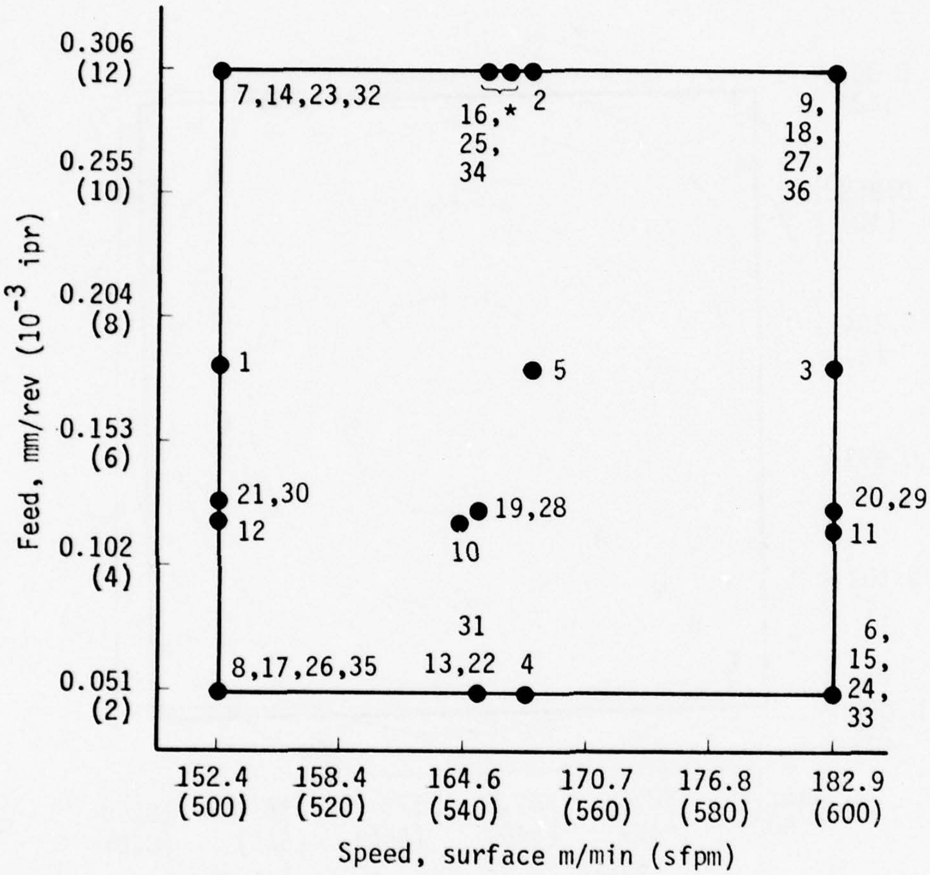


FIGURE 7d - CONTOURS OF CONSTANT VARIANCE OF PREDICTED LnT FOR Wu's SECOND-ORDER MODEL AFTER 9 TESTS BASED ON A CCD; LEVEL CODES: A = 0.50, B = 0.80, C = 1.50, D = 2.50



*Brackets indicate that specified tests were located within this interval.

FIGURE 8a - D-OPTIMAL TEST POINTS FOR NON-LINEAR MODEL: CASE I

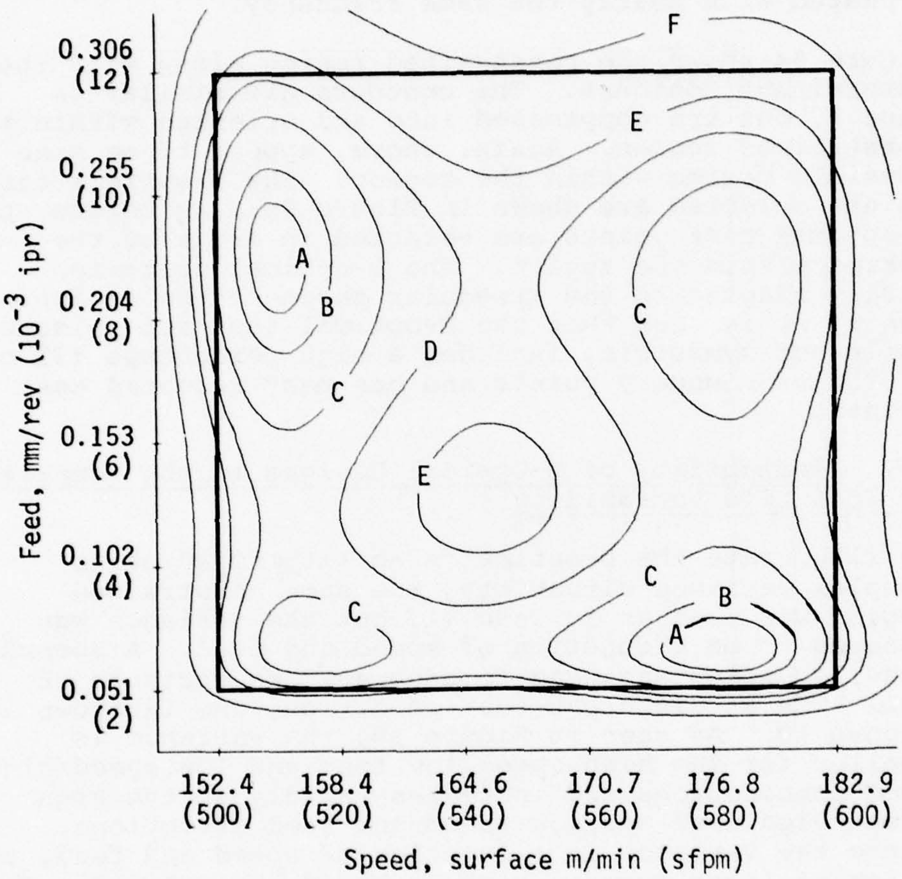


FIGURE 8b - CONTOURS OF CONSTANT $|\underline{X}^T\underline{X}|$ FOR NON-LINEAR MODEL AFTER 14 TESTS: CASE $\underline{I}$. LEVEL CODES: A = 0.1993, B = 0.1995, C = 0.2000, D = 0.2005, E = 0.2010, F = 0.2025.

increases rapidly at the boundaries and the D-optimal criterion attempts to minimize the maximum variance; (2) Many points are repeated thereby allowing estimates of the inherent process error to be obtained; (3) The points are somewhat evenly distributed near the areas of the nine local maxima of the determinant response function (shown in Figure 8b), i.e., points seem to be repeated with nearly the same frequency.

Figure 9a shows the constrained region along with the determinant contours. The contours are similar to Case I, but are compressed into and oriented within the constrained region. Again, there, appear to be nine possible maxima within the region. The D-optimal test points selected are shown in Figure 9b. As before, the D-optimal test points are selected in areas of the maxima within the region. The D-optimal criterion easily adapted to the irregular shape of the region. Again, it is seen that the D-optimal test set selected, while not symmetric, includes a high percentage (31 out of 35) of boundary points and has many repeated test points.

IV. Adaptability of D-Optimal Designs to the Complex Nature of Tool Life Variability

To illustrate the D-optimal's ability to adapt to complex variance situations, the same constrained region was used as in Case II, but the variance was assumed to be a function of speed and feed. A second-order equation was used to generate the variance of tool life at different test conditions and is shown in Figure 10. As seen in Figure 10, the variance is smaller for the high speed/low feed and low speed/high feed combinations and increases rapidly in the high speed/high feed and low speed/low feed directions. Since the variance is a function of speed and feed, the weighted least squares method should be employed. The D-optimal criterion for the weighted case is to maximize the determinant of the $X'W^{-1}X$ (weighted cross-product) matrix. The $|X'W^{-1}X|$ contours are shown in Figure 11a. The contours have shifted toward the lower variance test conditions within the region, but still have the same general shape. This is borne out in Figure 11b which presents the D-optimal test points for the weighted case. The test conditions specified have shifted to favor the smaller variance locations (high speed/low feed and low speed/high feed). It appears that a trade-off exists between properly selecting the tests within the region that are the most sensitive to the character of the model and running the tests in regions of expected higher precision.

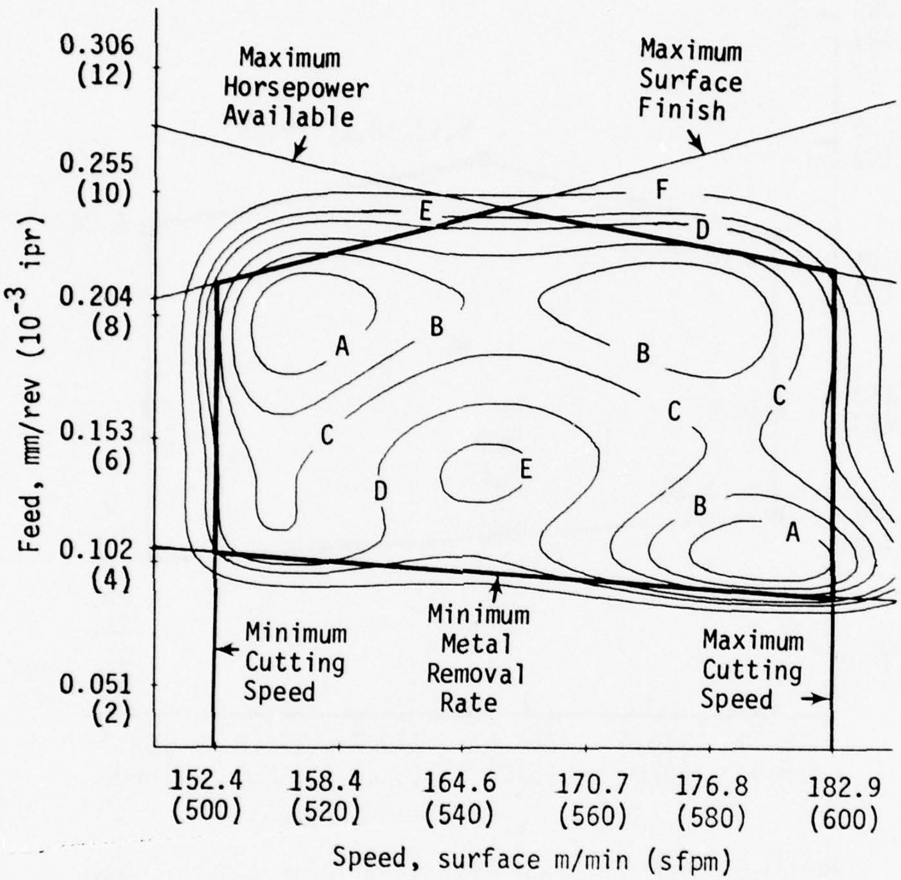
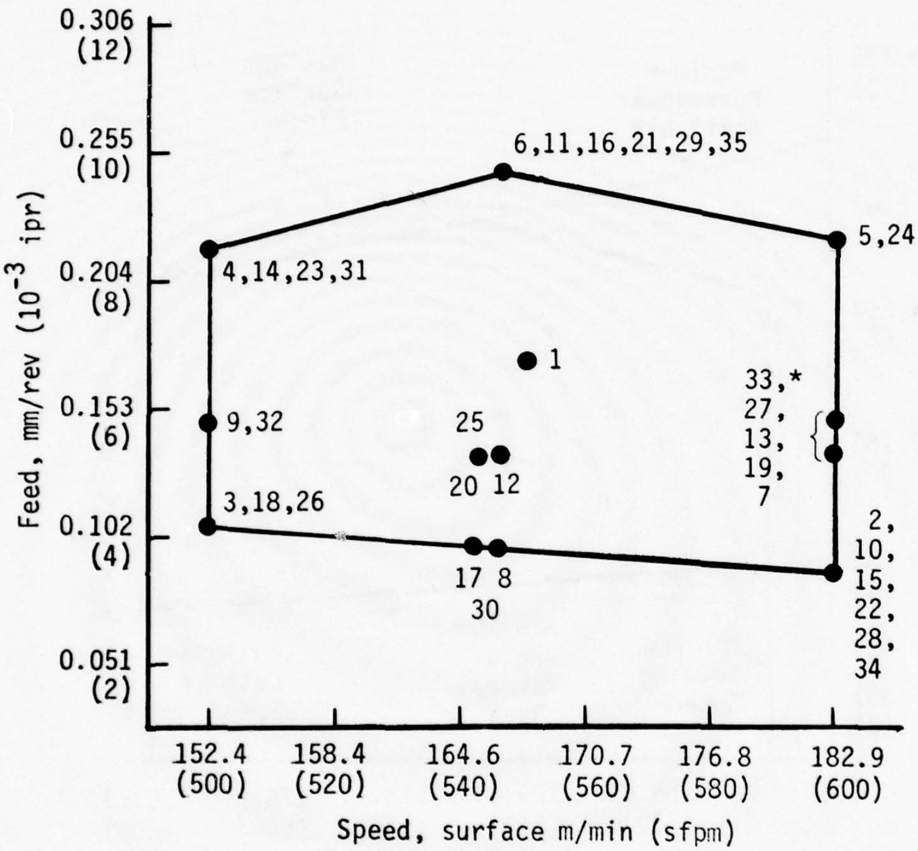


FIGURE 9a - CONTOURS OF CONSTANT $\left|\underline{X}^T\underline{X}\right|$ FOR THE NON-LINEAR MODEL AFTER 14 TESTS: CASE II. LEVEL CODES ($X10^{-3}$): A = 2.285, B = 2.290, C = 2.295, D = 2.303, E = 2.308, F = 2.320.



*Brackets indicate that specified tests were located within this interval.

FIGURE 9b - D-OPTIMAL TEST POINTS FOR NON-LINEAR MODEL: CASE II

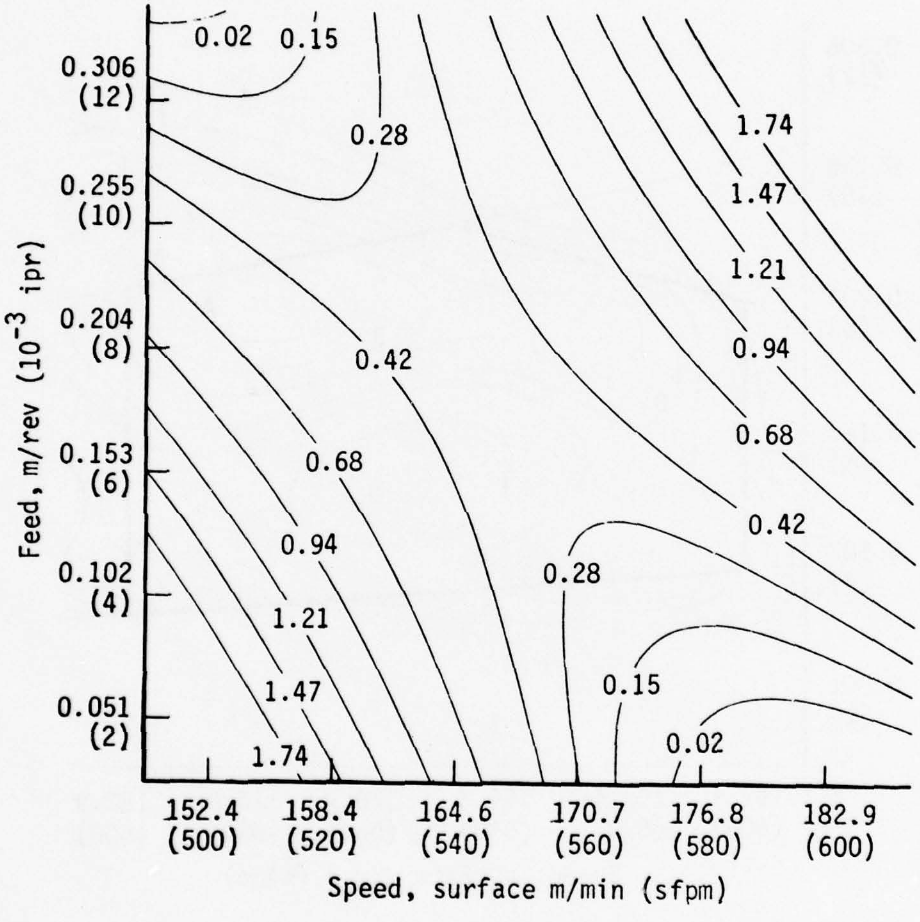


FIGURE 10 - VARIANCE RESPONSE SURFACE USED IN EXAMPLE IV

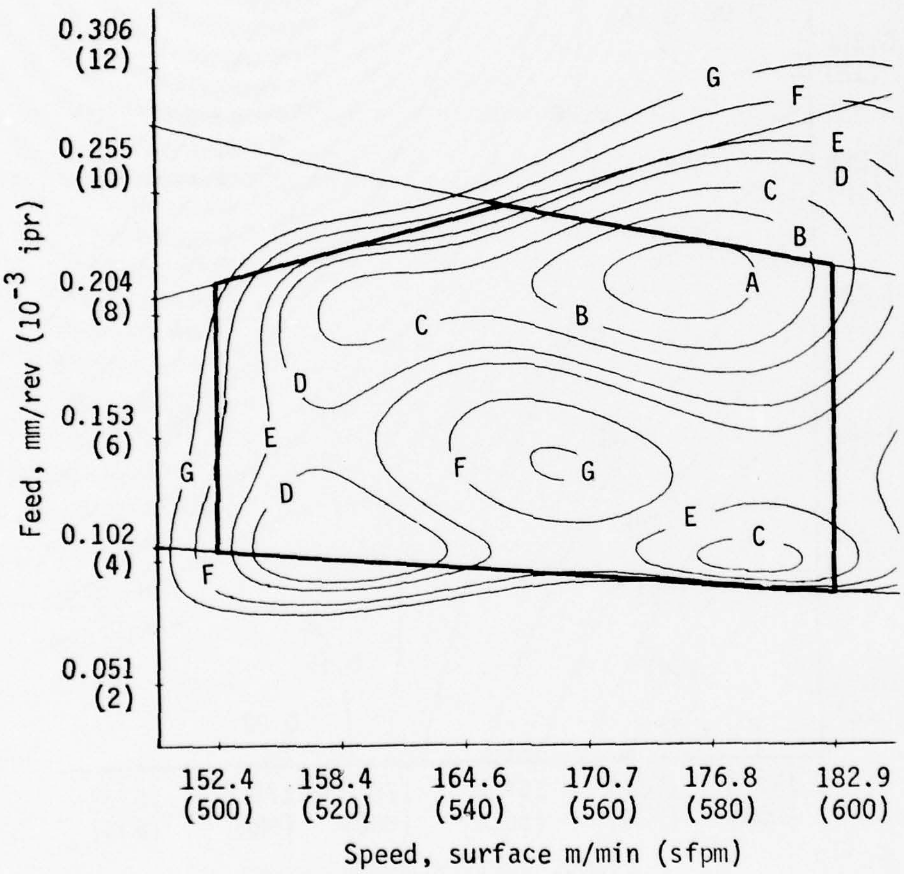
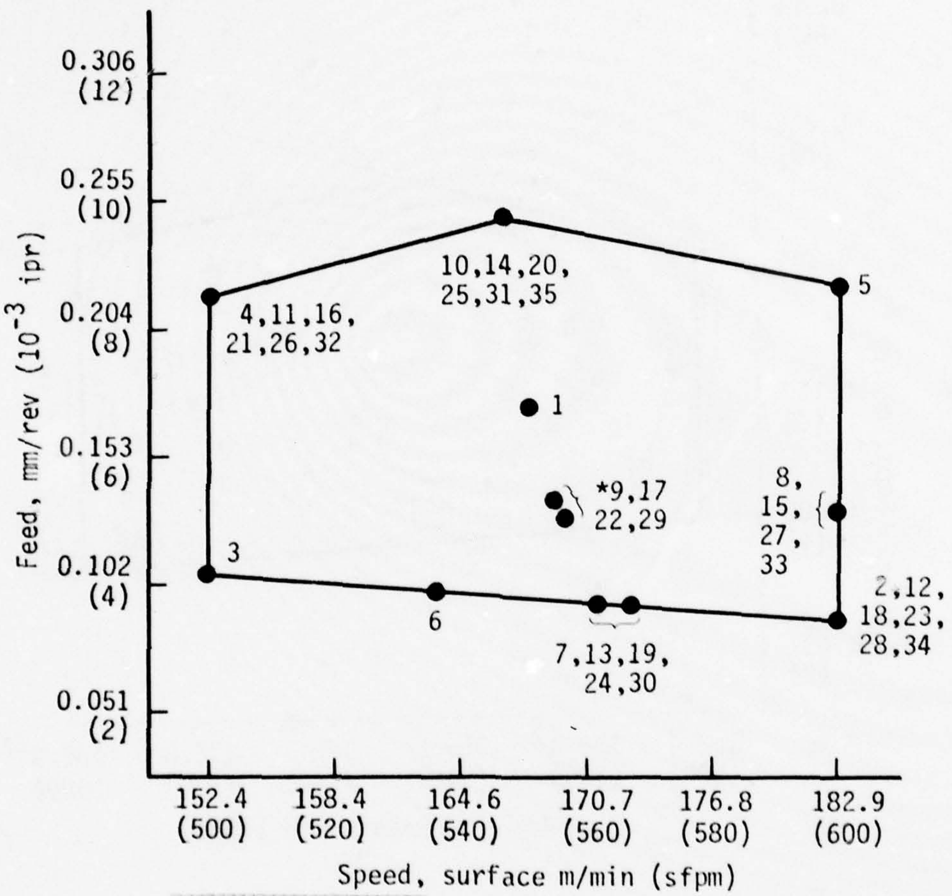


FIGURE 11a - CONTOURS OF CONSTANT $|\underline{X}^T W^{-1} \underline{X}|$ FOR THE NON-LINEAR MODEL AFTER 14 TESTS: LEVEL CODES (x 10^{-3})
A = 1.06, B = 1.08, C = 1.10, D = 1.13, E = 1.15, F = 1.20, G = 1.25.



*Brackets indicate that specified tests were located within this interval.

FIGURE 11b - D-OPTIMAL TEST POINTS FOR NON-LINEAR MODEL: INHOMOGENEOUS VARIANCE CASE

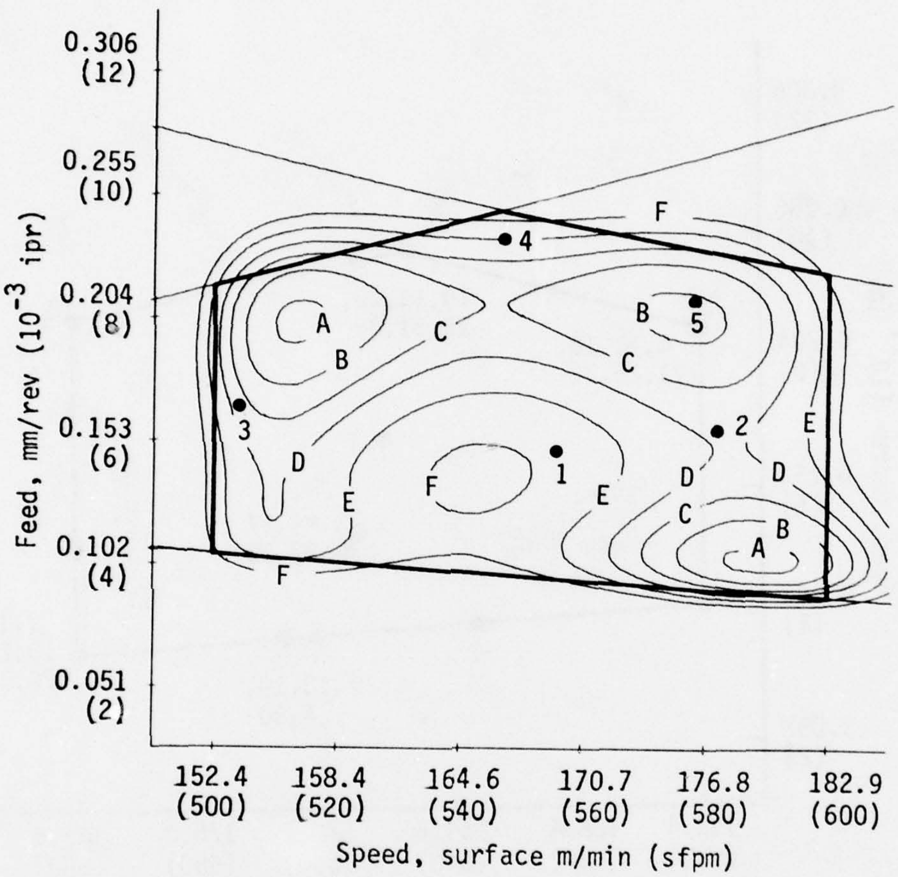


FIGURE 12a - CONTOURS OF CONSTANT VARIANCE OF PREDICTED LnT FOR CASE II AFTER 15 D-OPTIMAL TESTS; LEVEL CODES: A = 0.17, B = 0.20, C = 0.23, D = 0.26, E = 0.30, F = 0.35

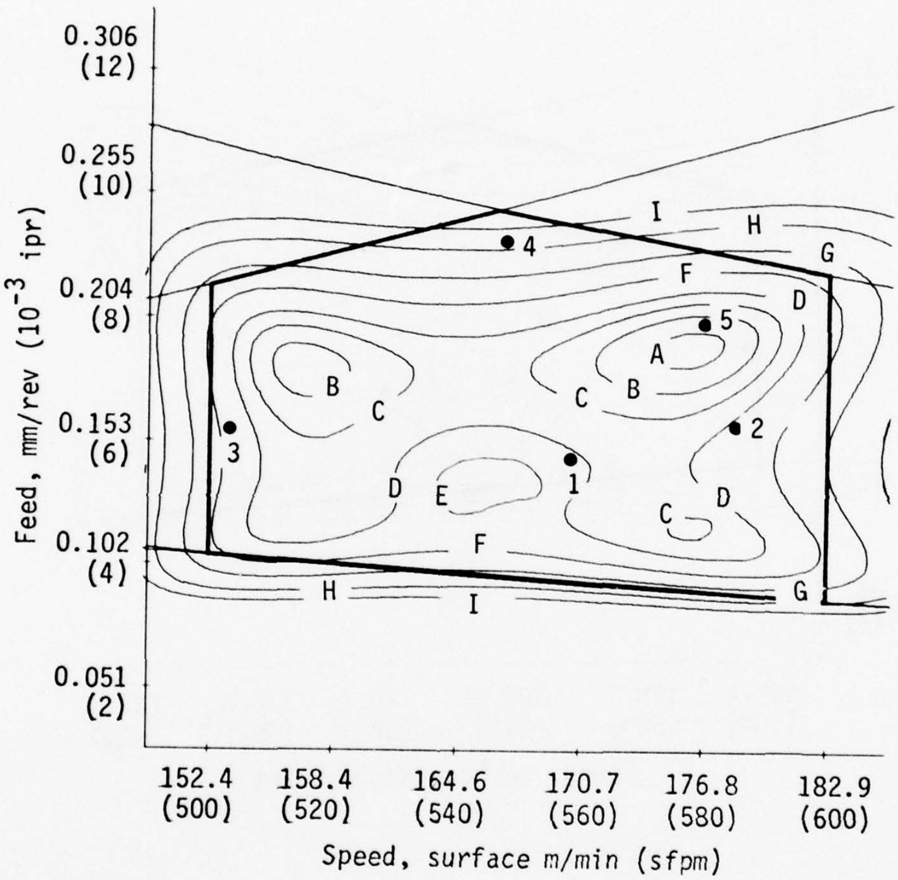


FIGURE 12b - CONTOURS OF CONSTANT VARIANCE OF PREDICTED LnT FOR CASE II AFTER 15 TESTS BASED ON A 3-LEVEL FACTORIAL DESIGN; LEVEL CODES: A = 0.155, B = 0.18, C = 0.21, D = 0.25, E = 0.28, F = 0.35, G = 0.50, H = 0.75, I = 1.0

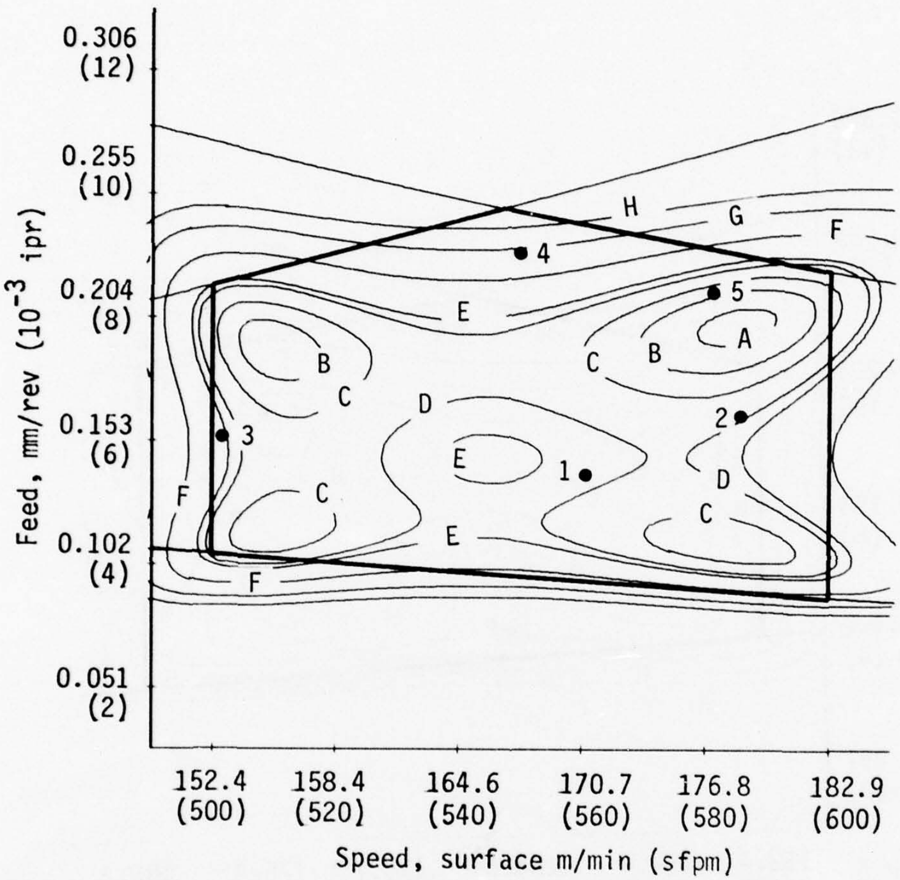


FIGURE 12c - CONTOURS OF CONSTANT VARIANCE OF PREDICTED LnT FOR CASE II AFTER 15 TESTS BASED ON A CCD; LEVEL CODES: A = 0.165, B = 0.20, C = 0.24, D = 0.30, E = 0.33, F = 0.50, G = 0.75, H = 1.0

V. Model Predictive Improvement Obtained With D-Optimal Designs

To illustrate the improved predictive capabilities obtained with the D-optimal design, a comparison between the D-optimal design, the 3-level factorial design and the CCD was performed for Case II. Figures 12a, 12b, and 12c show contours of constant variance for ln(T) for the three designs. The following observations can be made:

1. The 3-level factorial design and the CCD yield approximately comparable contours in shape and magnitude of the variance.

2. The D-optimal variance contours differ from those produced from the other designs in that a more pronounced interior maxima is observed. The general magnitudes are similar to the other designs toward the center of the region, but differ drastically as the boundaries are approached. The maximum variance is only 30 percent as large as the maximum variance obtained from the other designs.

3. The D-optimal design does not generate an improved variance throughout the region, for example, near the area of the interior maxima. The sizable variance improvement obtained along the boundaries of the region when D-optimal designs are employed is particularly significant since the optimal economic cutting condition often will be located on or near economic or operational constraints.

2.4.4 Tool Life Modeling Experimental Strategies

The determination of appropriate strageties for the design of machining experiments leading to mathematical modeling depends strongly on the objectives of the investigation at hand and preliminary knowledge of the nature of the experimental environment. The selection of the control variables under study, the region of interest of these variables and the appropriate mathematical models for both the basic response of interest and the constraints of the experimental environment have a strong influence on the experimental design strategy to be employed.

Once the objectives of the machining situation under study have been articulated and the experimental environment well defined, the development and implementation of tool life experimental strategies involves three stages:

Stage I: Selection of an Initial Set of Experiments

Stage II: Construction of the Feasibility Region for the Process Variables

Stage III: Determination of the Constrained Experimental Design Machining Tests

In Stage I, two questions need to be addressed; first, the number of initial tests required to adequately construct the feasible experimental region, and second, the placement of those tests in the controllable variable space so that constraint models are properly constructed and the responses observed are reasonable and, hopefully, near the eventual feasible region. The first question was addressed in Section 2.4.2 when the effect of degrees of freedom on probabilistic constraints was shown. It was seen that the minimum number of initial tests should be at least two more than the number of model parameters, i.e., $N_O \geq P + 2$. Furthermore, a minimum number of initial tests should be run since they would generally be non-optimal as determined by the experimental criterion. A possible strategy for the placement of the tests would be to place a full or fractional 2-level factorial design with optional center points about a recommended operating point. This recommended operating or base point can be obtained from current production practice or from recommendations in machinability data handbooks provided by tool manufacturers, material producers, or individual machinability research organizations. This base point would generally be feasible and near the eventual optimal region.

In Stage II, the data from the initial tests together with all other information on the machining process under study (process objectives, part requirements, machining environments) are used to construct the feasible region of study. Generally, a set of deterministic and probabilistic constraint equations are defined and fitted using the initial test data to construct this region. Such feasibility regions attempt to define the most desirable operating points based primarily on economic grounds and are generally of highly irregular shape and orientation in the independent variable space. For laboratory-based studies of a more fundamental nature, probabilisitic constraints should be based on

the distribution of the true mean and hence will yield larger feasible regions than for production situations where the distribution of the mean of future test realizations produce narrower feasible regions.

Once the feasible region of study has been defined, it remains to select and employ a design criterion to produce a series of machining tests. For studies of this nature, the appropriate model is generally known and interest focuses on precise parameter estimation for improved prediction capabilities. In this Stage III of the total methodology, the D-optimal design criterion appears to be well suited to the tool life situation. The emphasis on model precision is desirable for situations where the model form is known.

For broader tool life investigations where model discrimination needs to be done, a joint criterion consisting of both discrimination and precise parameter estimation can be defined. This joint criterion would shift the emphasis from discrimination to precise parameter estimation as a tool life model is decided upon. The specific details of this criterion would need to be developed for the tool life modeling environment.

Because of the nature of the D-optimal design criterion, tests may be planned and executed sequentially (one-at-a-time). When nonlinear models are being employed, this sequential approach is required. For linear models, theoretically all tests can be D-optimally planned in advance. However, because of the constraint modeling in addition to that for the primary process response (e.g., tool life), it may be more desirable to use a sequential strategy either one test at a time or in small groups. In this way, information from early tests can be employed to improve the precision related to the constraint modeling and therefore lead to better design of experiments toward the latter stages of the investigation. This may be especially important since the D-optimal criterion tends to select a large proportion of the tests at the constraints, i.e., the feasible region boundaries.

Initial investigations with the D-optimal experimental design criterion have revealed certain characteristic patterns of behavior with the test selection. This has lead to the suggestion that sub-optimal test arrangements could be easily identified and implemented without the need to mathematically evaluate the objective function

to exactly locate the optimal test location sequentially. For example, in irregularly shaped variable spaces, the D-optimal criterion chooses a high proportion of points at the constraint boundaries. For first order models, these points generally fall at the vertices of the constrained region. Hence, by simply employing a vertex design to specify the test points, a sub-optimal design arrangement can be developed with great simplicity. Further work is needed to study the degree of sub-optimality involved and the best strategies to employ when the number of tests needed is larger than K (the number of vertices), when second order or nonlinear models are used and when complex variance situations are encountered. Simplified designs, based on the D-optimal concept, should have particular utility in shop floor ongoing production situations.

For Stage III, various termination criteria need to be developed. For specific part/production investigations, the maximum variance of any predicted tool life within the final experimental region can be specified. For example, requiring an uncertainty of ± 20% in predicted tool life anywhere within the feasible experimental/production region is possible. Often the investigation termination criterion is predetermined by the economics of the experimentation. For example, material and tool quantities, allocated experimentation time, cost of labor, overhead on equipment, etc. could each determine an upper limit on the number of tests to be run. It is for this reason that the optimization of the experimental criteria to obtain the objective of the experimentation is important.

Figure 13 shows a flow chart to illustrate the design of the machining experiments methodology described above. Initial tests are defined based on machining data handbook guidance together with known operational and physical process constraints. Performance constraints may then be developed based on the data collected from these initial tests which indicate process results with respect to such performance measures as tool life, surface finish, horsepower requirements, etc. Once the constraints are used to construct the region of interest, further testing is specified with emphasis on precise modeling results and the development of baseline data for other uses in the future.

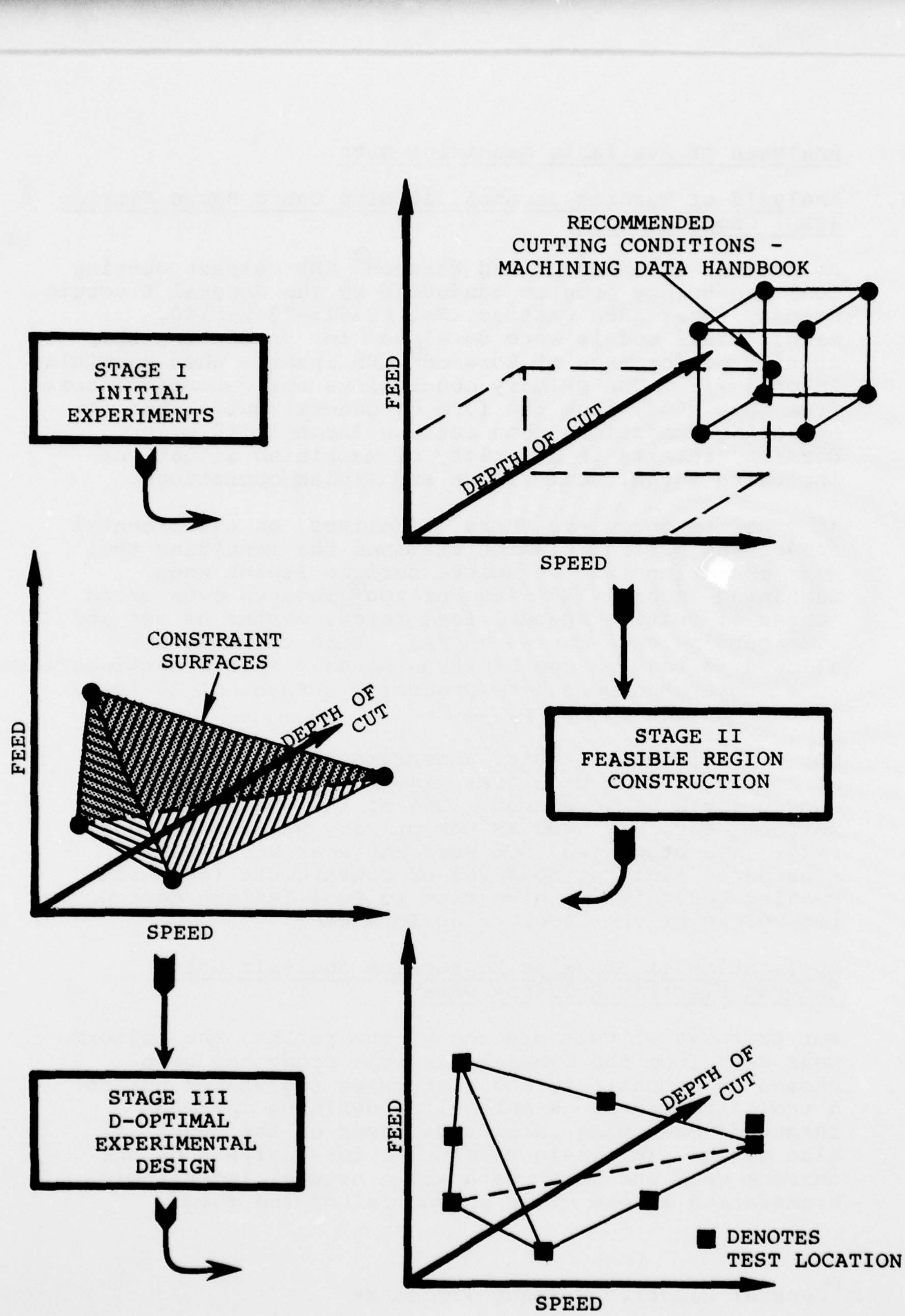


FIGURE 13 - TOOL LIFE MODELING EXPERIMENTAL STRATEGY

2.5 Analysis of Available Machining Data

2.5.1 Analysis of Turning Inconel 718 With Cubic Boron Nitride (CBN) Compact Tools

As part of the diamond and Borazon[T] CBN compact cutting tool technology program conducted by the General Electric Company under ARPA Contract No. F33615-73-C-5180, mathematical models were developed for predicting the cutting performance of Borazon[T] CBN inserts when machining Inconel 718. The primary conclusions and recommendations from this study took the form of general guidelines for operating conditions when cutting Inconel 718 with Borazon inserts in a variety of machining situations including rough, semi-finish and finish operations.

In order to formulate these guidelines, an experimental design was performed which examined the resulting tool wear conditions and workpiece surface finish when machining Inconel 718 with Borazon[T] inserts over broad ranges of cutting speeds, feed rates, depths of cut and side cutting edge angles (SCEA). Each variable was allowed to take on one of three equally spaced settings/levels in a cuboctahedron scheme producing a total of 36 tests including four center parts.

For each of the 36 tests, measurements of three types of tool wear were made over time so that typical wear curves could be developed. One of the wear measures, uniform wear, was used as the primary measure of tool life. The other two, DCL wear and wear back, were considered limiting measures or constraints for which cutting beyond would give rise to tool failure/destruction regardless of the level of uniform wear.

Application of Stepwise Regression Analysis Using General Electric Borazon[T] Data

For purposes of this section of the report, the uniform wear data from the General Electric study has been chosen to demonstrate how a stepwise regression builds a tool life model. A method for defining optimum ranges of machining parameters based on the model is also given. The basic model used for analysis of the uniform wear end point data was a natural logarithmic transformed second order polynomial of the form:

[T]General Electric Company Trademark

$$
\begin{aligned}
\ln TL = b_0 &+ b_1 \ln V + b_{11}(\ln V)^2 + b_{12}\ln V \ln f \\
& b_2 \ln f + b_{22} (\ln f)^2 + b_{13} \ln V \ln RD \\
& b_3 \ln RD + b_{33} (\ln RD)^2 + b_{14} \ln V \ln SC \\
& b_4 \ln SC + b_{44} (\ln SC)^2 + b_{23} \ln f \ln RD \\
& \qquad\qquad\qquad\qquad b_{24} \ln f \ln SC \\
& \qquad\qquad\qquad\qquad b_{34} \ln RD \ln SC
\end{aligned} \tag{28}
$$

where TL = tool life (time to 0.30 in. uniform wear); V = speed (fpm); f = feed (ipr); RD = radial depth of cut (in.); SC = side cutting edge angle (degrees); b_0, $b_1, \ldots, b_{34}$ are fitted coefficients.

Figure 14a shows the data input to the stepwise regression program. The first attempt to model the data yielded an obvious outlier data point which for this analysis has been deleted. Stepwise regression analysis chooses a subset of the terms of the basic model according to a partial F-level criterion. The program starts by choosing the most important term from the basic model and moving in a stepwise manner includes more terms until no more terms satisfy the user specified criterion. An example of the stepwise procedure is shown in Figures 14b through 14f. At some points in this procedure, terms that were considered important and included in the early stages were found to be unimportant and were removed again based on the partial F-level criterion. The result was a compact model which defines tool life as a function of machining parameters. As a check the model was then used to make predictions of tool life for the original test points. Figure 14g shows a comparison of the actual tool life from the tests with the tool life as predicted by the model.

The model resulting from the General Electric test program was as follows:

$$
\begin{aligned}
\ln TL = -29.4488 &+ 13.5834 \ln V -1.4303(\ln V)^2 -0.0926\ln f \ln V \\
&+ 3.6995 \ln RD -0.6091 \ln RD \ln V
\end{aligned} \tag{29}
$$

The log residual standard deviation was 0.1898 with a square of the multiple correlation coefficient of 0.9600. This was interpreted to say that 96% of the variation of the data was explained by the model. It is interesting to note that the SCEA did not appear in the resulting model. This means that the SCEA was not significant at the user chosen 95% level.

In order to appreciate what the model was saying, plots were necessary. Figures 15a, 15b, and 15c are plots of the resulting model. They were constructed with lines of constant tool life on plots of feed versus speed. The plots show that any combination of feed and speed that falls on a given constant tool life line will yield the same near tool life. The radial depth and SCEA were constant for each individual plot. Since the SCEA was not used in the model, plots for different SCEA values were unnecessary.

As an aid in recommending economic operating regions, lines of constant material removal rate have been overlaid on the feed versus speed plots. Since these lines usually do not run parallel to the constant tool life lines, it can be seen that for different combinations of feed and speed at a constant material removal rate, different tool life will result. Therefore, barring any constraints such as surface finish requirements, for any desired material removal rate, the speed and feed should be selected so as to maximize the tool life. The points of maximum tool life for each specific material removal rate form a line which we call the R-T-F curve. A detailed description of this concept may be found in two papers by Friedman and Tipnis (1976). Relative to this data analysis, the R-T-F curve is very speed specific. At a radial depth of 0.01 in., the R-T-F concept points to an optimum speed of about 450 sfpm. As the radial depth increases, the R-T-F curve moves to lower speeds until at a 0.08 in. depth of cut, the R-T-F curve moves beyond the range of the test data. Once the general location of the R-T-F curve has been identified more specific tests in this range might be run to pinpoint its location. This, then, becomes another factor in the step-by-step design of experiments.

2.5.2 Comparison of Tool Life Experimental Strategies Through Simulation

Computer simulation of the tool life experimental environment was used to develop and test various experimental strategies for tool life modeling. This procedure employed a "basic-model", developed for each process response from actual machining data, to simulate the behavior of the response at various test points within the experimental region. Using simulation to evaluate various strategies provided a consistent experimental environment. Unbiased evaluations of the strategies

	V	F	RD	SC	TL
1	900.0000	0.0060	0.0800	15.0000	2.7000
2	900.0000	0.0080	0.0450	45.0000	3.6000
3	900.0000	0.0040	0.0800	30.0000	4.3000
4	600.0000	0.0060	0.0450	30.0000	16.0000
5	300.0000	0.0040	0.0450	45.0000	46.0000
6	300.0000	0.0060	0.0100	45.0000	21.6000
7	900.0000	0.0040	0.0100	30.0000	7.0000
8	900.0000	0.0060	0.0100	15.0000	9.0000
9	300.0000	0.0040	0.0800	30.0000	35.6000
10	600.0000	0.0080	0.0100	15.0000	19.4000
11	600.0000	0.0040	0.0800	45.0000	15.2000
12	600.0000	0.0040	0.0800	15.0000	16.7000
13	300.0000	0.0060	0.0800	15.0000	37.0000
14	600.0000	0.0040	0.0100	45.0000	20.4000
15	600.0000	0.0080	0.0800	15.0000	6.3000
16	600.0000	0.0060	0.0450	30.0000	12.0000
17	900.0000	0.0040	0.0450	45.0000	5.8000
18	300.0000	0.0080	0.0100	30.0000	17.0000
19	600.0000	0.0060	0.0450	30.0000	11.0000
20	600.0000	0.0080	0.0100	45.0000	15.5000
21	300.0000	0.0060	0.0800	45.0000	53.2000
22	900.0000	0.0080	0.0100	30.0000	7.1000
23	600.0000	0.0080	0.0800	45.0000	10.0000
24	600.0000	0.0060	0.0450	30.0000	13.3000
25	900.0000	0.0060	0.0800	45.0000	3.6000
26	600.0000	0.0040	0.0100	15.0000	20.9000
27	300.0000	0.0040	0.0450	15.0000	41.6000
28	900.0000	0.0040	0.0450	15.0000	5.5000
29	300.0000	0.0060	0.0100	15.0000	32.5000
30	300.0000	0.0080	0.0450	45.0000	28.4000
31	300.0000	0.0080	0.0450	15.0000	26.0000
32	900.0000	0.0080	0.0800	30.0000	2.2000
33	900.0000	0.0080	0.0450	15.0000	2.9000
34	900.0000	0.0060	0.0100	45.0000	6.8000
35	300.0000	0.0040	0.0100	30.0000	25.2000

FIGURE 14a - EXAMPLE OF STEPWISE REGRESSION ANALYSIS PROGRAM OUTPUT FOR BORAZON® TURNING OF INCONEL 718

BZN TURNING SQUARE TOOLS INCONEL 718

```
REGRESSION ANALYSIS
DEPENDENT VARIABLE                    TL
RESIDUAL STANDARD DEVIATION       0.4163
STANDARD ERROR OF THE MEAN        0.0704
MULTIPLE R                        0.8838
MULTIPLE RSQR                     0.7811

VARIABLE ENTERED                   SQV
```

VARIABLE	B - COEF	STD ERR OF B	PARTIAL-R	BETA-COEF	STD ERR BETA
SQV	-0.1365	0.0126	-0.8838	-0.8838	0.0814

CONSTANT 7.9896

ANALYSIS OF VARIANCE TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARE	F
MEAN	1	0.22109E+03	0.22109E+03	
REGRESSION	1	0.20404E+02	0.20404E+02	0.11776E+03
ERROR	33	0.57179E+01	0.17327E+00	

PARTIAL-F OF LEAST SIGNIFICANT VARIABLE IN MODEL IS 117.7590
PARTIAL-F OF MOST SIGNIFICANT VARIABLE NOT IN MODEL IS 7.3994

FIGURE 14b - EXAMPLE OF STEPWISE REGRESSION ANALYSIS PROGRAM OUTPUT FOR BORAZON® TURNING OF INCONEL 718

AD-A053 339 METCUT RESEARCH ASSOCIATES INC CINCINNATI OHIO F/G 13/8
MATHEMATICAL MODELING OF MATERIAL REMOVAL PROCESSES FOR IMPROVE--ETC(U)
SEP 77 V A TIPNIS, S A VOGEL, S C BUESCHER F33615-76-C-5254
UNCLASSIFIED 1566-23599 AFML-TR-77-154 NL

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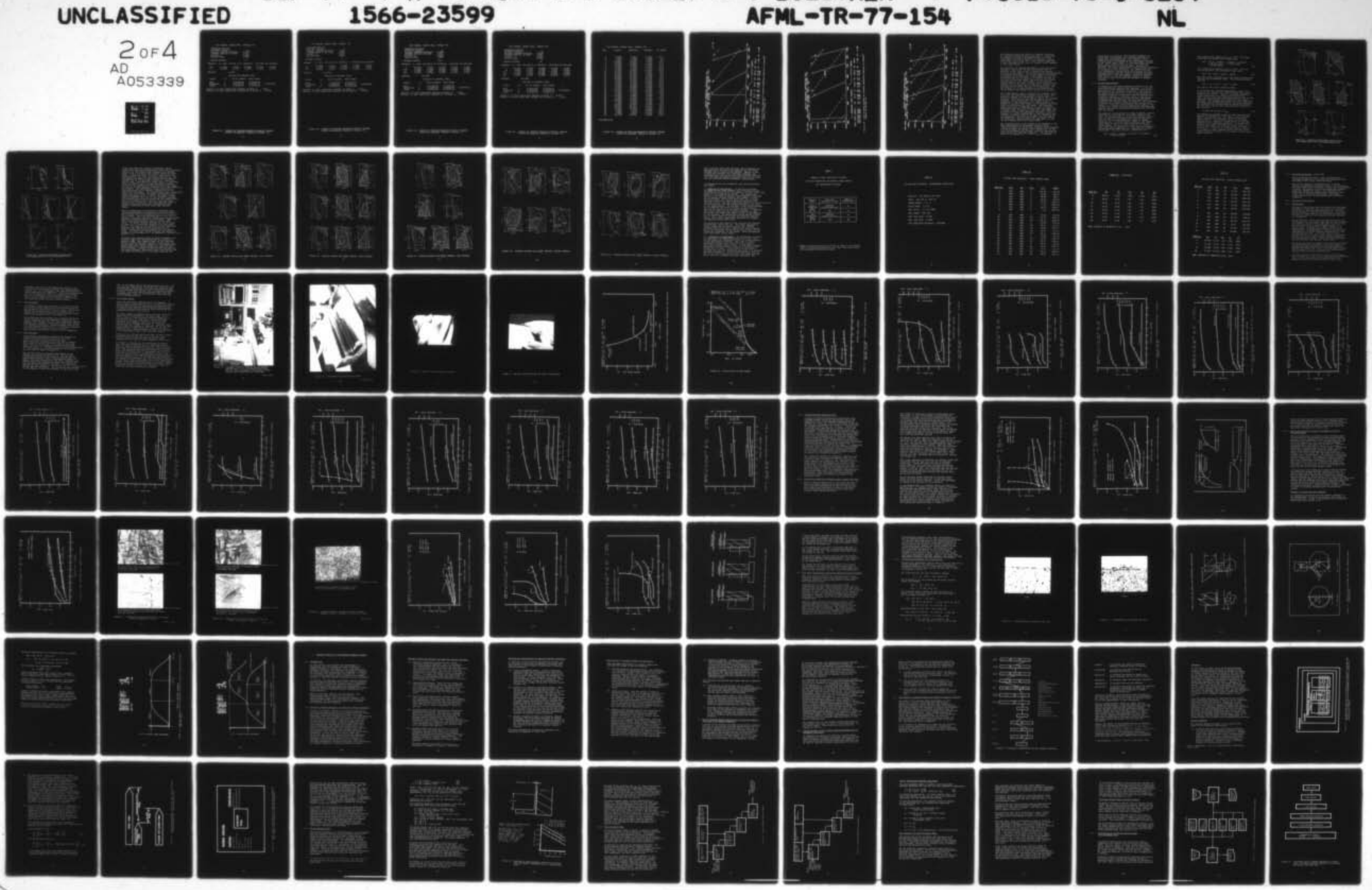


BZN TURNING SQUARE TOOLS INCONEL 718

REGRESSION ANALYSIS	
DEPENDENT VARIABLE	TL
RESIDUAL STANDARD DEVIATION	0.3810
STANDARD ERROR OF THE MEAN	0.0644
MULTIPLE R	0.9068
MULTIPLE RSQR	0.8222

VARIABLE ENTERED F V

VARIABLE	B - COEF	STD ERR OF B	PARTIAL-R	BETA-COEF	STD ERR BETA
SQV	-0.1756	0.0184	-0.8600	-1.1372	0.1193
F V	-0.0978	0.0359	-0.4334	-0.3245	0.1193

CONSTANT 6.3704

ANALYSIS OF VARIANCE TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARE	F
MEAN	1	0.22109E+03	0.22109E+03	
REGRESSION	2	0.21478E+02	0.10739E+02	0.73997E+02
ERROR	32	0.46440E+01	0.14513E+00	

PARTIAL-F OF LEAST SIGNIFICANT VARIABLE IN MODEL IS 7.3994
PARTIAL-F OF MOST SIGNIFICANT VARIABLE NOT IN MODEL IS 8.5528

FIGURE 14c - EXAMPLE OF STEPWISE REGRESSION ANALYSIS PROGRAM OUTPUT FOR BORAZON® TURNING OF INCONEL 718

BZN TURNING SQUARE TOOLS INCONEL 718

REGRESSION ANALYSIS

DEPENDENT VARIABLE	TL
RESIDUAL STANDARD DEVIATION	0.3427
STANDARD ERROR OF THE MEAN	0.0579
MULTIPLE R	0.9277
MULTIPLE RSQR	0.8607

VARIABLE ENTERED V

VARIABLE	B - COEF	STD ERR OF B	PARTIAL-R	BETA-COEF	STD ERR BETA
V	15.9665	5.4595	0.4650	8.2891	2.8343
SQV	-1.4550	0.4378	-0.5126	-9.4207	2.8345
F V	-0.0965	0.0323	-0.4726	-0.3204	0.1073

CONSTANT -43.1406

ANALYSIS OF VARIANCE TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARE	F
MEAN	1	0.22109E+03	0.22109E+03	
REGRESSION	3	0.22482E+02	0.74940E+01	0.63826E+02
ERROR	31	0.36398E+01	0.11741E+00	

PARTIAL-F OF LEAST SIGNIFICANT VARIABLE IN MODEL IS 8.5528
PARTIAL-F OF MOST SIGNIFICANT VARIABLE NOT IN MODEL IS 7.9978

FIGURE 14d - EXAMPLE OF STEPWISE REGRESSION ANALYSIS PROGRAM OUTPUT FOR BORAZON® TURNING OF INCONEL 718

BZN TURNING SQUARE TOOLS INCONEL 718

REGRESSION ANALYSIS

DEPENDENT VARIABLE	TL
RESIDUAL STANDARD DEVIATION	0.3095
STANDARD ERROR OF THE MEAN	0.0523
MULTIPLE R	0.9434
MULTIPLE RSQR	0.8900

VARIABLE ENTERED RDV

VARIABLE	B - COEF	STD ERR OF B	PARTIAL-R	BETA-COEF	STD ERR BETA
V	16.0824	4.9314	0.5116	8.3492	2.5602
SQV	-1.4716	0.3955	-0.5620	-9.5283	2.5605
F V	-0.0989	0.0292	-0.5259	-0.3284	0.0970
RDV	-0.0267	0.0094	-0.4588	-0.1762	0.0623

CONSTANT -43.8638

ANALYSIS OF VARIANCE TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARE	F
MEAN	1	0.22109E+03	0.22109E+03	
REGRESSION	4	0.23248E+02	0.58120E+01	0.60675E+02
ERROR	30	0.28737E+01	0.95790E-01	

FARTIAL-F OF LEAST SIGNIFICANT VARIABLE IN MODEL IS 7.9978
FARTIAL-F OF MOST SIGNIFICANT VARIABLE NOT IN MODEL IS 50.7965

FIGURE 14e - EXAMPLE OF STEPWISE REGRESSION ANALYSIS PROGRAM OUTPUT FOR BORAZON® TURNING OF INCONEL 718

BZN TURNING SQUARE TOOLS INCONEL 718

REGRESSION ANALYSIS	
DEPENDENT VARIABLE	TL
RESIDUAL STANDARD DEVIATION	0.1898
STANDARD ERROR OF THE MEAN	0.0321
MULTIPLE R	0.9798
MULTIPLE RSQR	0.9600

VARIABLE ENTERED RD

VARIABLE	B - COEF	STD ERR OF B	PARTIAL-R	BETA-COEF	STD ERR BETA
V	13.5834	3.0440	0.6380	7.0518	1.5803
RD	3.6995	0.5191	0.7979	3.7517	0.5264
SGV	-1.4303	0.2425	-0.7384	-9.2609	1.5704
F V	-C.0926	0.0179	-0.6923	-0.3075	0.0595
RDV	-C.6091	0.0819	-0.8099	-4.0214	0.5409

CONSTANT -29.4488

ANALYSIS OF VARIANCE TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARE	F
MEAN	1	0.22109E+03	0.22109E+03	
REGRESSION	5	0.25077E+02	0.50155E+01	0.13927E+03
ERROR	29	0.10444E+01	0.36013E-01	

PARTIAL-F OF LEAST SIGNIFICANT VARIABLE IN MODEL IS 19.9128
PARTIAL-F OF MOST SIGNIFICANT VARIABLE NOT IN MODEL IS 4.8157

FIGURE 14f - EXAMPLE OF STEPWISE REGRESSION ANALYSIS PROGRAM OUTPUT FOR BORAZON® TURNING OF INCONEL 718

BZN TURNING SQUARE TOOLS INCONEL 718

CASE	ACTUAL	PREDICTED	RESIDUAL	PCT ERROR
1	2.7001	3.0404	-0.3403	-12.6
2	3.5999	3.2733	0.3265	9.1
3	4.2999	3.9256	0.3743	8.7
4	16.0002	12.8820	3.1182	19.5
5	45.9981	41.0366	4.9615	10.8
6	21.6001	23.5914	-1.9913	-9.2
7	6.9999	9.8722	-2.8723	-41.0
8	8.9998	7.6461	1.3537	15.0
9	35.5984	46.7275	-11.1291	-31.3
10	19.4005	14.5991	4.8015	24.7
11	15.2001	14.6303	0.5698	3.7
12	16.6999	14.6303	2.0696	12.4
13	36.9993	37.7157	-0.7164	-1.9
14	20.3993	22.0153	-1.6160	-7.9
15	6.2997	9.7018	-3.4021	-54.0
16	11.9999	12.8820	-0.8821	-7.4
17	5.8002	5.0664	0.7338	12.7
18	16.9998	20.2646	-3.2648	-19.2
19	11.0001	12.8820	-1.8819	-17.1
20	15.4994	14.5991	0.9003	5.8
21	53.2022	37.7157	15.4865	29.1
22	7.1000	6.3783	0.7218	10.2
23	10.0001	9.7018	0.2983	3.0
24	13.3005	12.8820	0.4185	3.1
25	3.5999	3.0404	0.5595	15.5
26	20.8990	22.0153	-1.1163	-5.3
27	41.6000	41.0366	0.5634	1.4
28	5.4997	5.0664	0.4333	7.9
29	32.4987	23.5914	8.9073	27.4
30	28.4003	28.4514	-0.0511	-0.2
31	26.0001	28.4514	-2.4513	-9.4
32	2.2001	2.5363	-0.3362	-15.3
33	2.9000	3.2733	-0.3734	-12.9
34	6.7998	7.6461	-0.8462	-12.4
35	25.1989	29.2284	-4.0295	-16.0

JOB COMPLETED

FIGURE 14g - EXAMPLE OF STEPWISE REGRESSION ANALYSIS PROGRAM OUTPUT FOR BORAZON® TURNING OF INCONEL 718

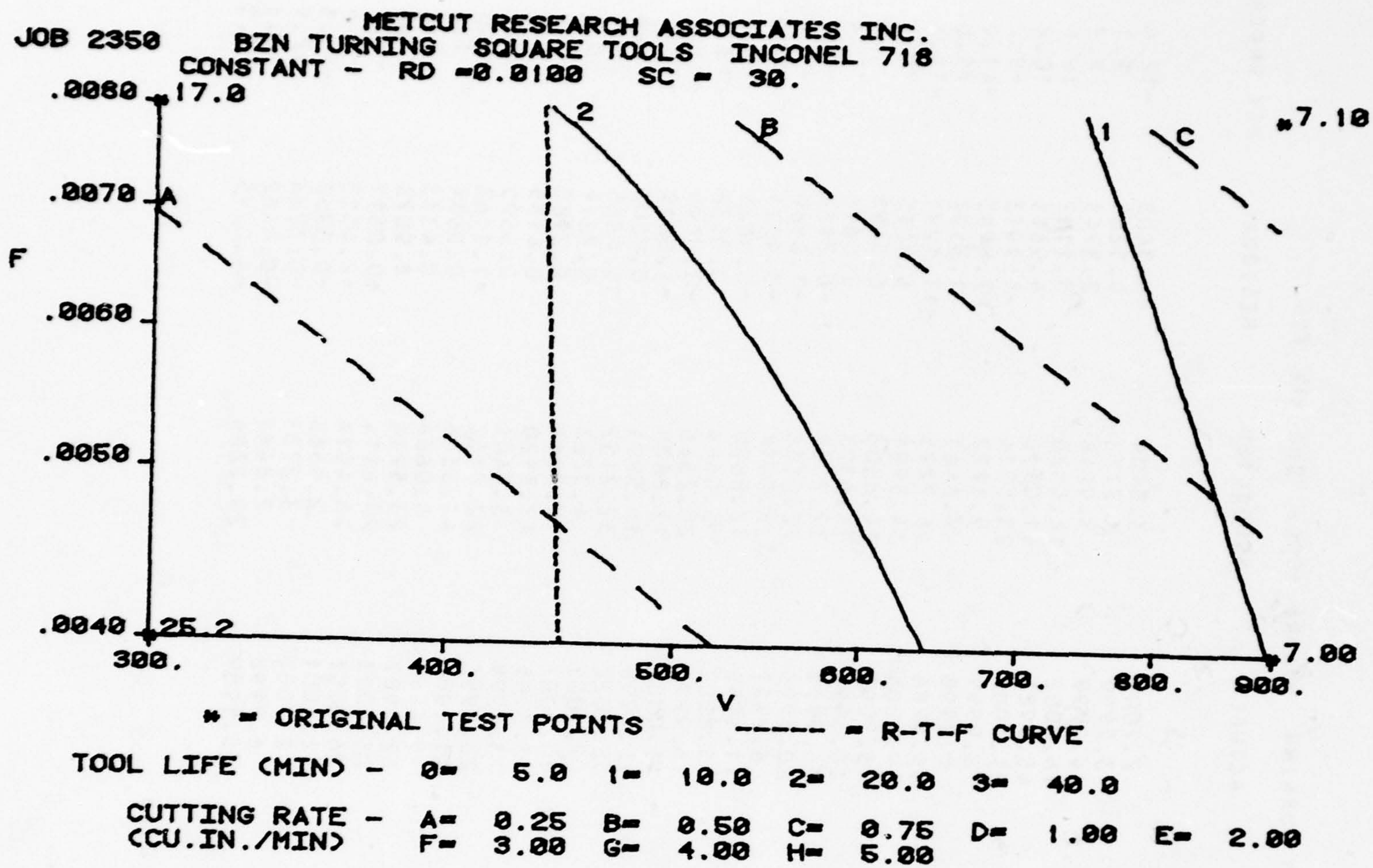


Figure 15a -PLOT OF MODEL PRODUCED BY STEPWISE REGRESSION ANALYSIS OF BORAZON®
TURNING OF INCONEL 718

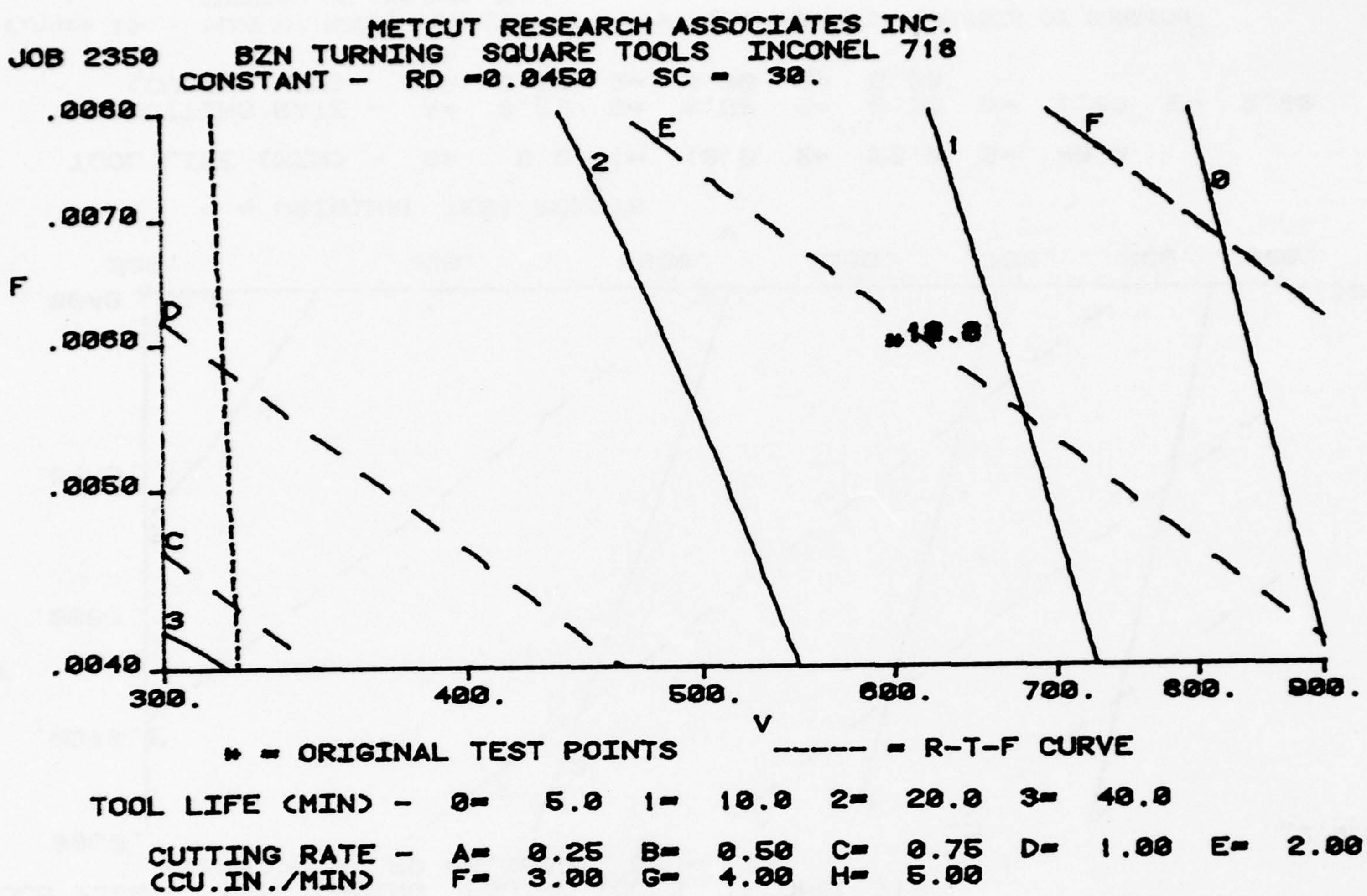


Figure 15b - PLOT OF MODEL PRODUCED BY STEPWISE REGRESSION ANALYSIS OF BORAZON® TURNING OF INCONEL 718

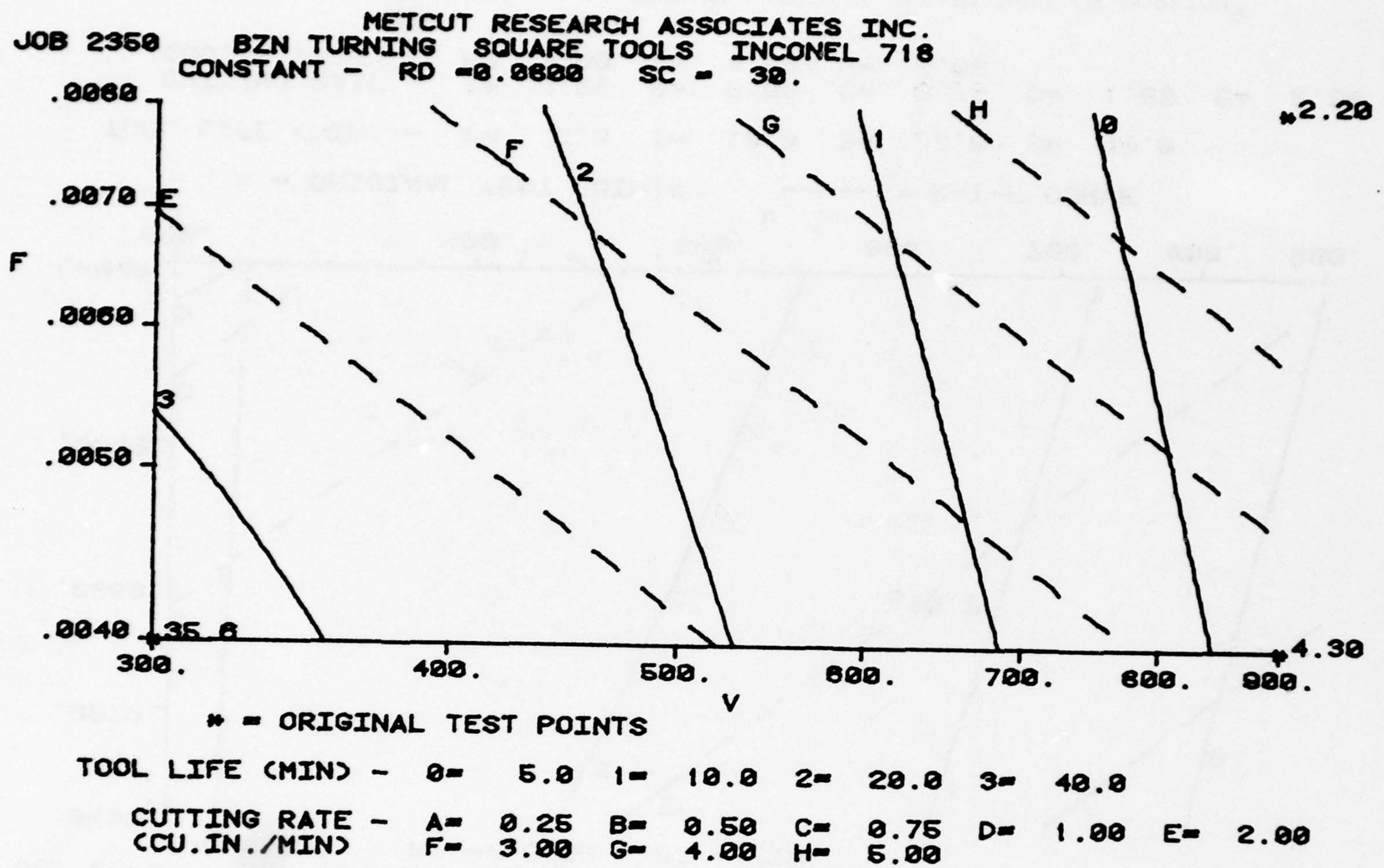


Figure 15c - PLOT OF MODEL PRODUCED BY STEPWISE REGRESSION ANALYSIS OF BORAZON® TURNING OF INCONEL 718

were obtained since the effects of unknown influences on response performance were eliminated or controlled. For example, physical disturbances found in actual experimentation such as material differences, ambient conditions, time trends, etc., were removed completely or were included in the level of random "noise" imbedded in the "basic model".

The simulation of various strategies is also much less expensive. Aside from the physical savings such as material, tools, labor, etc., a savings can also be realized in the study of the feasibility and appropriateness of proposed strategies. First, any number of different strategies can be evaluated. Minor aspects of various strategies such as the range of a certain variable in the initial factorial design can be easily and clearly evaluated while every other aspect of the strategy remains exactly the same. Second, each strategy can be evaluated for as many tests as necessary. Finally, any strategy can be easily verified by re-simulating, and the sensitivity of each strategy to such factors as "basic models" and random noise levels can be checked.

The "basic models" used to simulate the response (tool life) and the constraints (surface finish, force, etc.) should be general and "universal" in nature and, if possible, different from the models used in the proposed strategy. This insures that the estimation of the parameters in the strategy is not unduly biased. An example of a good "basic model" is the general nonlinear Konig and DePiereux tool life model. The nonlinear models are rarely recommended to be used in specific part/production tool life studies since they apply over a broader range of machining conditions and suffer the difficulty of obtaining parameter estimates. Often a response is clearly represented by only one model, and finding a different model to be used as a "basic model" is impossible. This is particularly true for some of the constraint responses where the same model is used in the strategy and as the "basic model."

The characteristics of the random noise imbedded in the "basic model" should be consistent with the actual observed behavior of the process response being simulated. A study by Wager and Barash (1971) showed that for the tool life response, the inherent variation was normally distributed with expected value zero. The variance was shown to be related as $\sigma^2 = K^2\bar{T}^2$, i.e., a constant

coefficient of variation. This variation behavior in actual tool life results in a constant variance for logarithmic transformed tool life. Commonly, this variance level is estimated by the mean square residual of the fitted "basic model" in log-transformed variable space. More recent studies of tool life variation (Friedman and Zlatin, 1974 and DeVor, Anderson and Zdeblick, 1976) have demonstrated a non-constant coefficient of variation in tool life data. For these situations, it is necessary to determine how the variance of the response behaves over the range of variables and imbed this behavior in the "basic model". Machining responses other than tool life are commonly assumed to behave similarly to tool life where the variance is assumed constant.

2.5.3 End Milling Analysis

To demonstrate the ideas presented in Section 2.4, the rough end milling operation was analyzed. A tool life and cutting force simulator was developed from actual machining data to perform the analysis. The purpose of the analysis was two-fold: first, to investigate the procedure necessary to construct feasible laboratory or production regions of operation and to illustrate the properties and behavior of these regions; and second, to demonstrate two different tool life experimental strategies and evaluate their performance. The strategies differed only in their selection of the initial tests (Stage I). A better understanding of the impact of the initial test selection on the experimental strategy was obtained and general guidelines concerning the selection were put forth.

The analysis was performed for three variables, cutting velocity (V), feed rate (f) and radial depth of cut (RD). The axial depth of cut was not included since it was felt that this variable would often be specified based on the part configuration, number of passes required, etc. Previous studies (Tipnis) also showed axial depth of cut to be less significant than the three chosen. The basic models used in the simulator were taken from a previous Air Force study performed by Metcut Research Associates Inc. (Contract No. F33615-74-C-5025). The tool life "basic model" used was:

$$\begin{aligned} LnT \quad & -28.06 + 14.83LnV - 1.78(LnV)^2 - .39(LnRD)^2 \\ & +.39(Lnf)(LnRD) \end{aligned} \qquad (30)$$

with random noise added as NID $(0, .24^2)$. The basic model for the cutting force response was

$$\begin{aligned} LnF = 21.19 &- 4.98LnV - 1.26LnRD + .56(LnV)^2 \\ &+ .095(LnV)(Lnf) - .17(Lnf)(LnAD) \\ &+ .39(LnV)(LnRD) \end{aligned} \tag{31}$$

with random noise added as NID $(0, .08^2)$. For the milling analysis, the linearized Taylor model

$$LnT = b_0 + b_1 LnV + b_2 Lnf + b_3 LnRD \tag{32}$$

was used as the D-optimal tool life objective model and the tool life constraint model. The linearized power function

$$LnF = \alpha_0 + \alpha_1 LnV + \alpha_2 Lnf + \alpha_3 LnRD \tag{33}$$

was used as the force constraint model.

To illustrate the feasible experimental region, the eight initial tests of the first strategy were used to construct the region. Table II lists the constraint limits under which this region was constructed. Table III lists the test conditions used for the initial tests and the simulated tool life and force values obtained. The minimum and maximum tool life constraint was constructed probabilistically; the force constraint was stochastic but constructed non-probabilistically, and the metal removal rate constraint was deterministic and given as:

$$15.28(F)(f)(RD)(AD) \geq R_{MIN} \tag{34}$$

The maximum and minimum limits for each variable were selected corresponding to the range of each variable used to develop the tool life and force simulator "basic models". The feasible region can be viewed physically as a volume in 3-space whose surfaces are defined by the constraint equations. To graphically present this volume, feasible areas were drawn in the velocity-feed plane for different values of radial depth of cut. Each of the following figures consists of a number of these feasible areas which should be viewed as being "stacked" on one another in the radial depth direction.

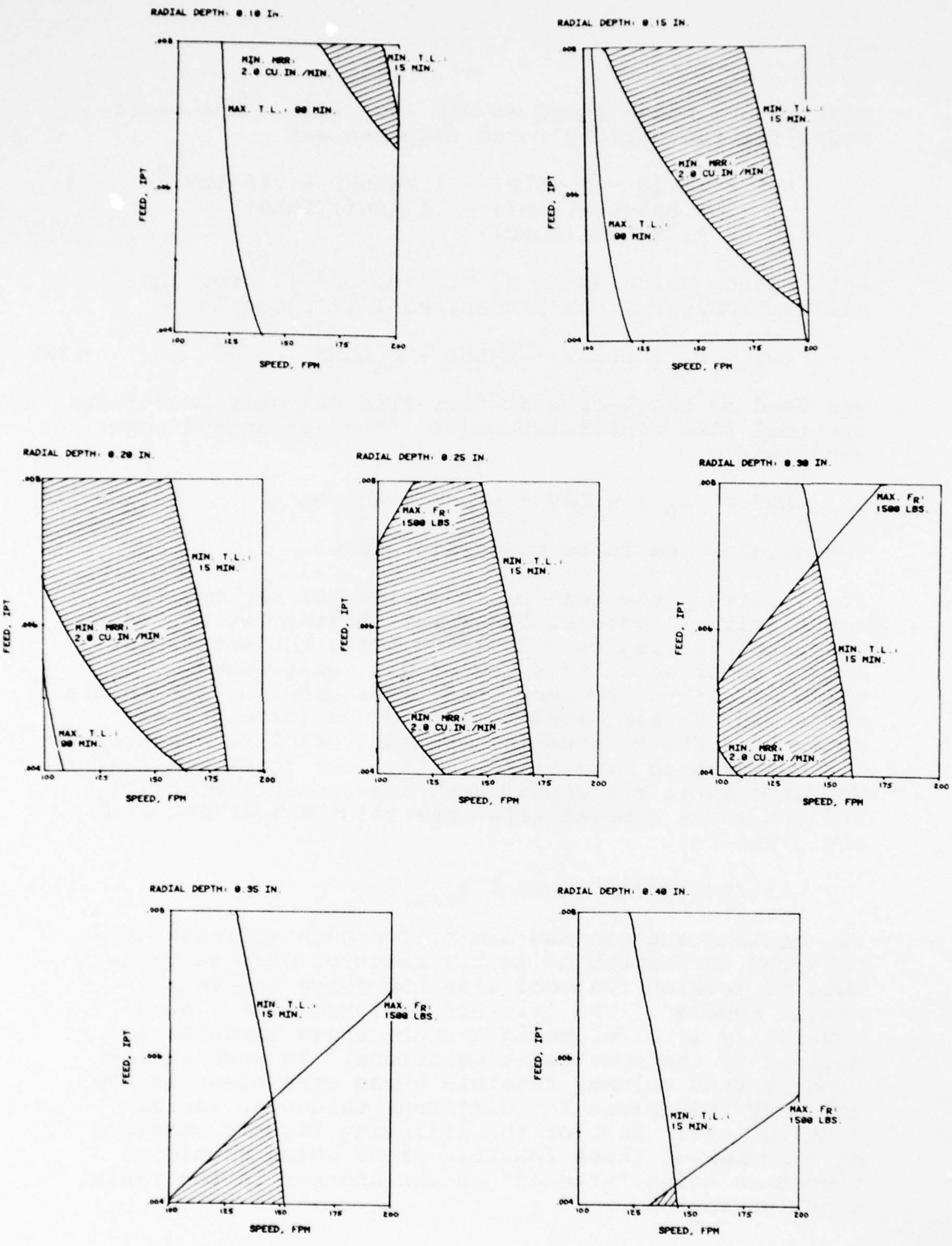


FIGURE 16a - FEASIBLE EXPERIMENTAL REGIONS USING 95% PROBABILISTIC TOOL LIFE CONSTRAINTS ON $\hat{Y}_o$

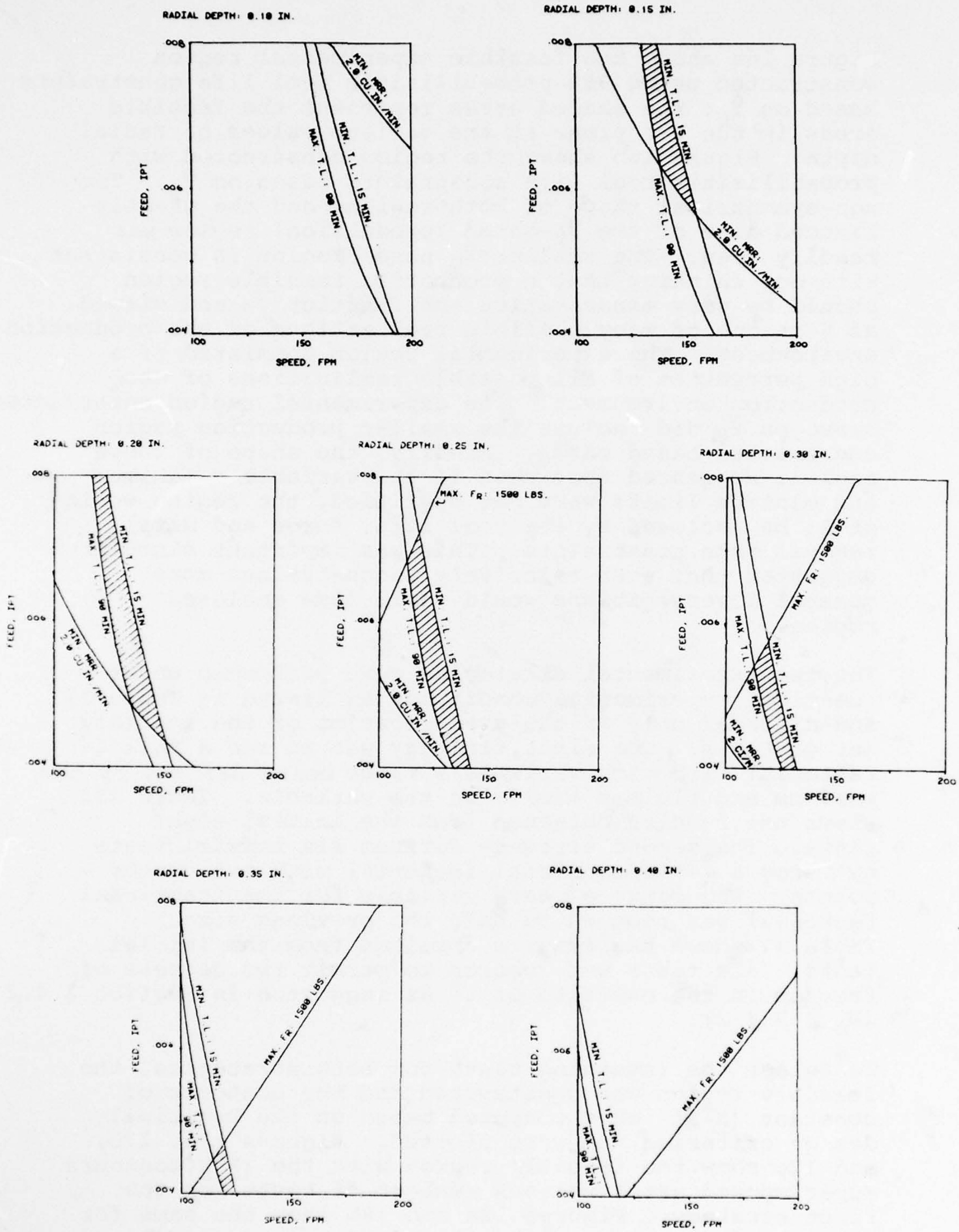


FIGURE 16b - FEASIBLE EXPERIMENTAL REGIONS USING 95% PROBABILISTIC TOOL LIFE CONSTRAINTS ON $\overline{Y}_O$

Figure 16a shows the feasible experimental region constructed using 95% probabilisitic tool life constraints based on $\hat{Y}_0$. The shaded areas represent the feasible areas in the V-f plane at the various values of radial depth. Figure 16b shows the region constructed with probabilisitic tool life constraints based on $\bar{Y}_0$. The non-symmetrical shape of both regions and the greatly reduced size of the $\bar{Y}_0$-based (production) region was readily seen. The smaller $\bar{Y}_0$ based region is consistent with our thinking that a production feasible region should be very conservative and restrictive and viewed as just one of many possible realizations of the production environment. The experimental region consisted of a high percentage of all possible realizations of the production environment. The experimental region constructed based on $\hat{Y}_0$ did include the smaller production region constructed based on $\bar{Y}_0$. Finally, the shape of these regions suggested that even if the variable's maximum and minimum limits were not specified, the region would still be enclosed by the tool life, force and metal removal rate constraints. This was important since it suggested that even relatively unconstrained more general investigations would yield some enclosed region.

The two experimental strategies were performed under identical experimental conditions as listed in Table II and differed only in the specification of the initial set of tests. The first strategy was to run a full 2^3 factorial with each variable's range being defined by the maximum and minimum limits on the variable. Table III shows the results obtained from the initial eight tests. The second stragety defined six initial tests by using a 2^{3-1} fractional factorial with two center points. The range of each variable for the fractional factorial was reduced to half the previous size. Table IV shows the results obtained from the initial tests. Six tests were chosen to permit two degrees of freedom in the estimate of σ^2 as suggested in Section 2.4.2 ($N_o \geq P + 2$).

To select the remaining tests for both strategies, the feasible region was constructed and the contours of constant $|\underline{X}^T\underline{X}|$ were computed based on the D-optimal design criterion and were plotted. Figures 17a, 17b, and 17c show the feasible region with the $|\underline{X}^T\underline{X}|$ contours superimposed after various numbers of tests for the first strategy. Figures 18a and 18b show the same for the second strategy. With the aid of a grid search over the region and the plots of the $|\underline{X}^T\underline{X}|$ contours, the

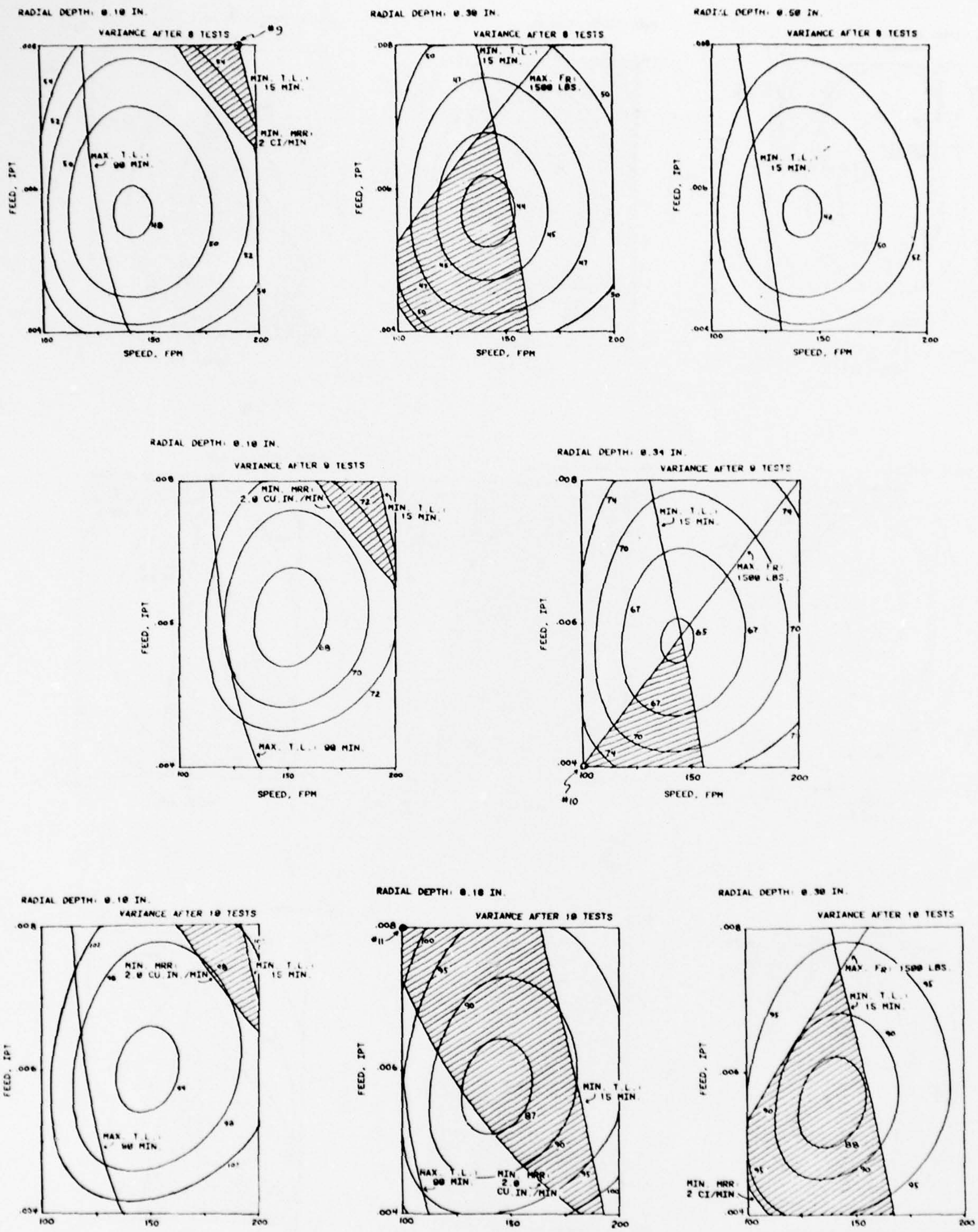


FIGURE 17a - FEASIBLE REGIONS WITH $|\underline{X}^T\underline{X}|$ CONTOURS, FIRST STRATEGY

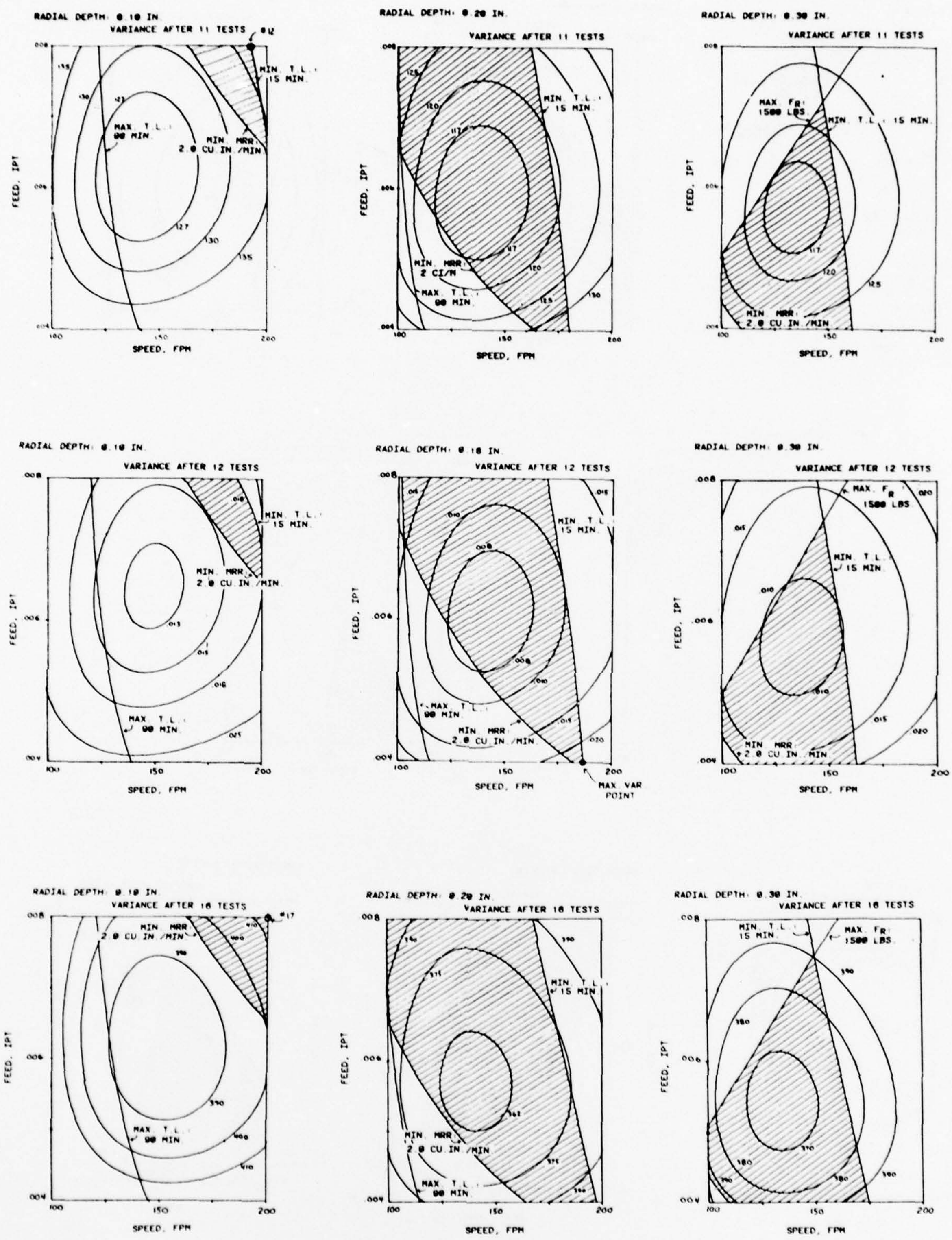


FIGURE 17b - FEASIBLE REGIONS WITH $|\underline{X}^T\underline{X}|$ CONTOURS, FIRST STRATEGY

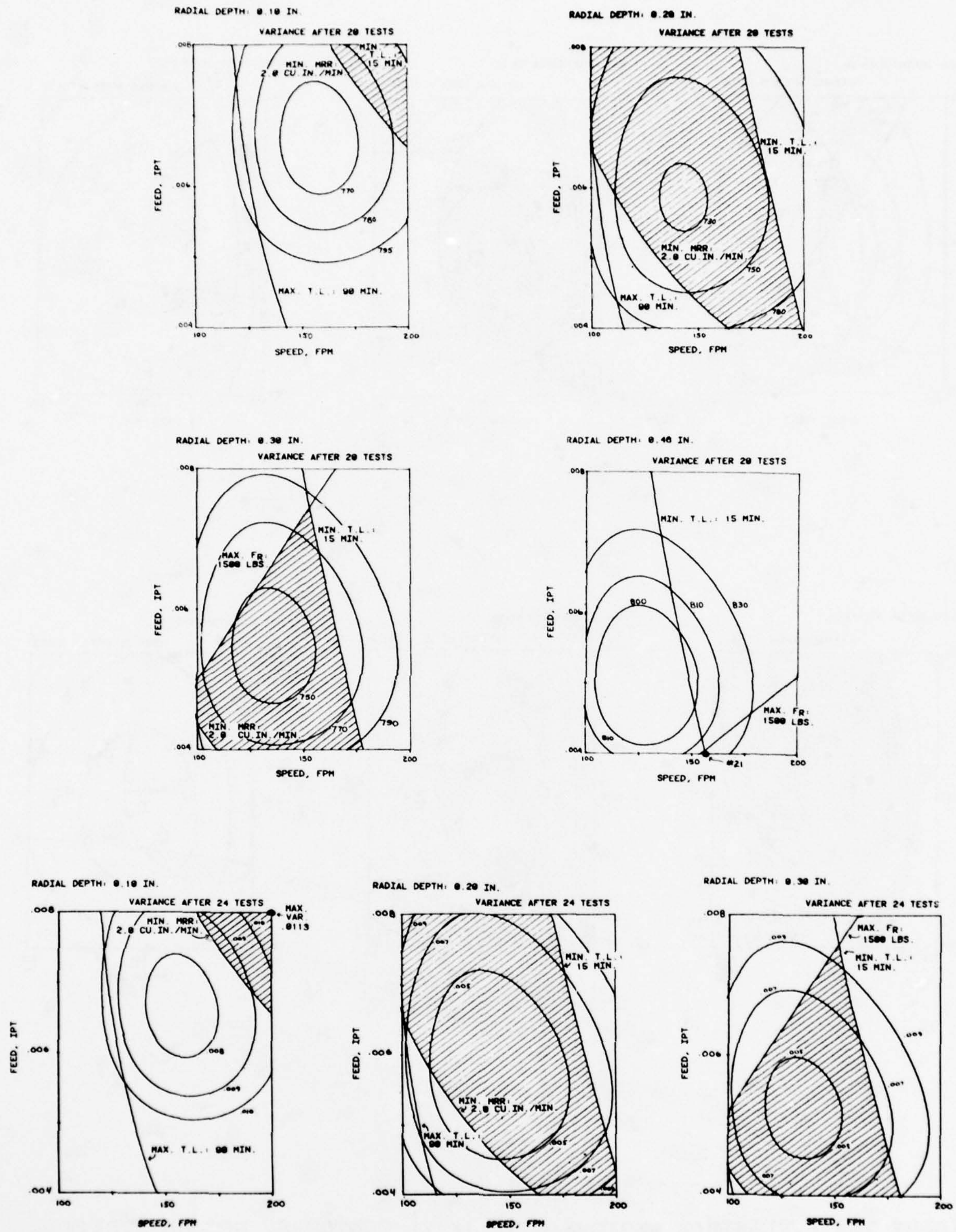


FIGURE 17c - FEASIBLE REGIONS WITH $|\underline{X}^T\underline{X}|$ CONTOURS, FIRST STRATEGY

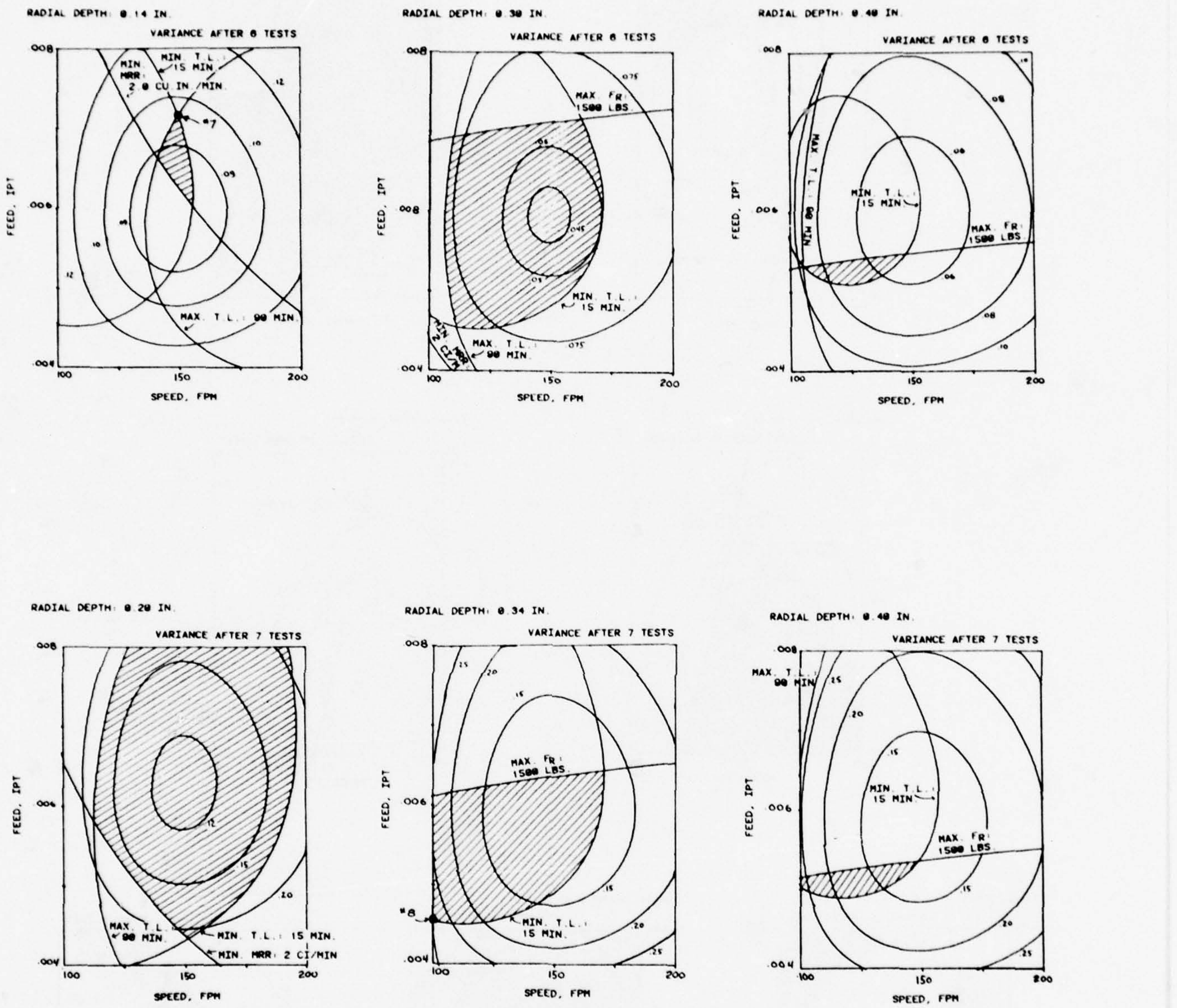


FIGURE 18a - FEASIBLE REGIONS WITH $|\underline{X}^T\underline{X}|$ CONTOURS, SECOND STRATEGY

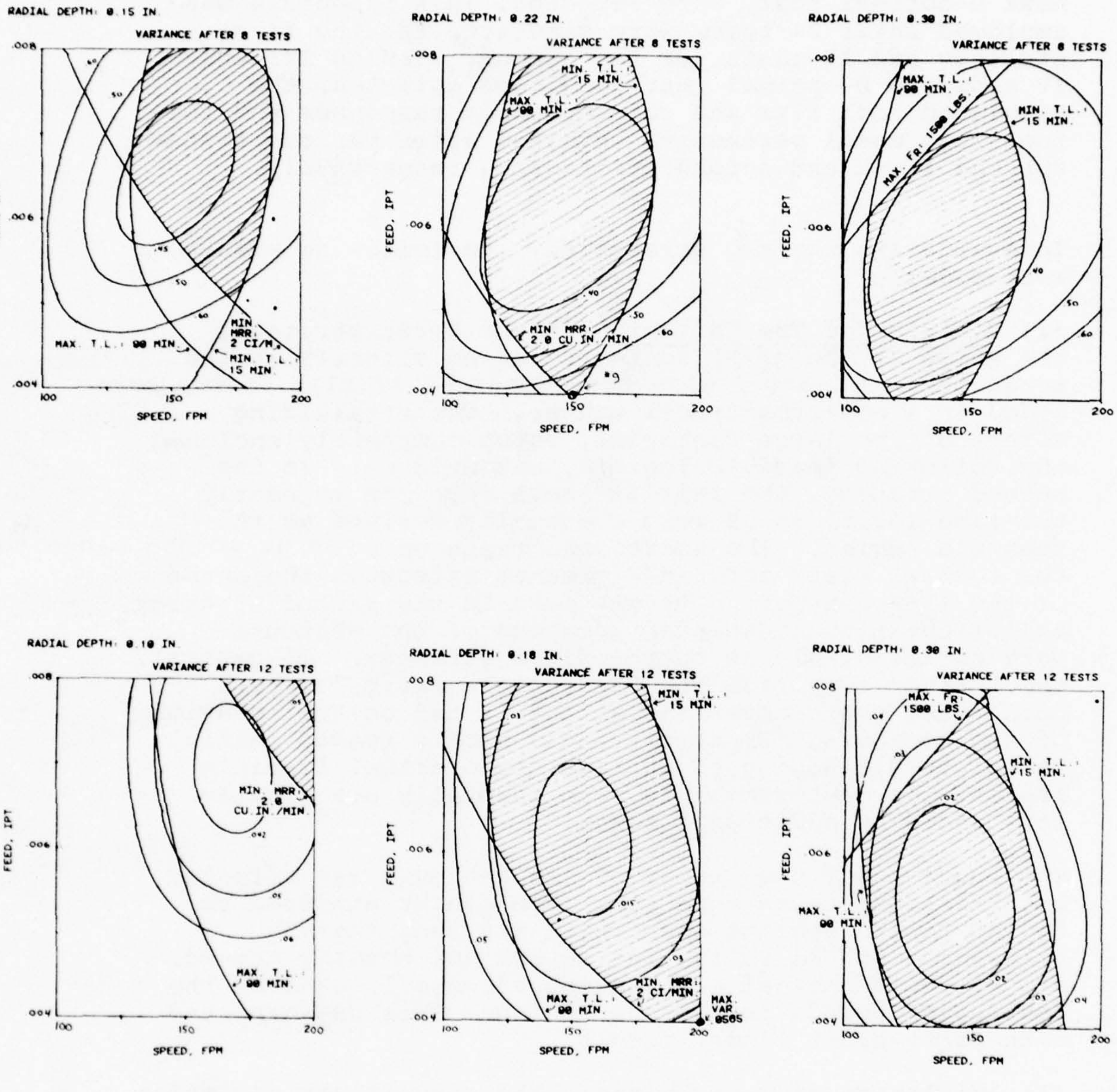


FIGURE 18b - FEASIBLE REGIONS WITH $|\underline{X}^T\underline{X}|$ CONTOURS, SECOND STRATEGY

next D-optimal tests were selected. This procedure was employed until 24 tests were simulated for the first strategy and 12 tests for the second. Tables III and IV show the D-optimal test conditons selected, the simulated tool life and cutting force responses and the tool life model parameters obtained after various tests for the first and second strategies, respectively.

In evaluating the two strategies, the following points were made:

(1) Behavior of The Contour: In the first strategy, the shape of the $|X^TX|$ contours varied slightly as the 16 additional tests (twice the number of initial tests) were added in a non-symmetrical manner. The stabilizing effect of the large factorial, which completely enclosed the following feasible regions, was evident. In the second strategy, the initial tests were run in nearly the same locations as were eventually defined as the feasible region. The additional tests were run at points close to the initial tests and had a greater effect on the shape of the $|X^TX|$ contours. As was seen in the second strategy, the orientation and center location of the contours were not as stable as in the first strategy. In general, the further away from the "center-of-gravity" a test point was, the greater the effect it had on the behavior of the contours. By specifying a widely spaced initial set of tests, hoping to enclose the eventual feasible region, the contour shapes were generally not greatly influenced by additional tests.

The location of the center of the contours was affected as additional tests were run. The center appeared to "move" toward regions where were are run, thereby allowing tests to be run in regions not heavily tested. All of the D-optimal tests selected were located on the constraint boundaries of the region. This was expected with first-order linear models.

(2) Violation of Constraints: The significant violation of constraints in specifying both the initial tests and the additional constrained tests, is a major concern in the experimental strategy. The risk of running unfeasible initial tests increased significantly with widely spaced initial tests. In the first strategy, employing the large factorial design to determine the initial set of tests, 3 out of the 8 initial tests violated the tool life constraint and 4 out of 8 violated the force constraint. In the second strategy, none of the initial tests violated the tool life constraint and only 2 out of 6 violated the force constraint, and

TABLE I

NUMBER OF TESTS REQUIRED TO ACHIEVE
SPECIFIED PRECISION FOR VARIOUS LINEAR MODELS
AND EXPERIMENTAL DESIGNS

Tool Life Model	(Tool Life) Experimental Design	Number of Required Tests*
Taylor's Linearized Model Eq. (3)	D-Optimal (2-Level Factorial)	17
	CCD	47
Wu's Second-Order Model Eq. (4)	D-Optimal (3-Level Factorial)	27
	CCD	60

* Number of tests required to achieve at least a ± 20 percent level of precision in any predicted tool life value within the rectangular operability region.

TABLE II

MILLING TEST SIMULATOR: EXPERIMENTAL CONDITIONS

VELOCITY: 100 SfPM TO 200 SfPM

FEED: .004 IPT to .008 IPT

RADIAL DEPTH: .1 TO .5

AXIAL DEPTH: 1.0 IN.

MIN. M.R.R.: 2.0 $IN.^3$/MIN.

MAX. FORCE: 1500 LBS.

MAX. TOOL LIFE: 90 MIN.

MIN. TOOL LIFE: 15 MIN.

TEST SELECTION CRITERION: D-OPTIMAL

TABLE III

MILLING TEST SIMULATOR: FIRST STRATEGY DATA

TEST NO.	VEL.	FD.	R.D.	T.L.	FORCE
1	100.	.004	.1	163.04	651.78
2	200.	.004	.1	24.99	407.32
3	100.	.008	.1	69.86	938.5
4	200.	.008	.1	26.05	599.93
5	100.	.004	.5	40.25	1717.97
6	200.	.004	.5	7.67	1865.49
7	100.	.008	.5	31.07	2336.17
8	200.	.008	.5	5.13	2143.10
9	190	.008	.1	17.07	530.60
10	100	.004	.34	69.73	1406.19
11	100	.008	.18	113.73	1420.48
12	190	.008	.1	22.00	549.82
13	185	.004	.18	28.59	603.32
14	100	.004	.34	74.23	1377.8
15	195	.004	.18	30.57	637.19
16	100	.008	.18	98.74	1392.84
17	200	.008	.1	17.80	562.60
18	150	.004	.44	25.58	1520.92
19	100	.008	.22	78.67	1610.47
20	200	.008	.1	15.73	641.29
21	155	.004	.46	14.57	1253.11
22	200	.004	.18	33.73	591.79
23	100	.004	.34	70.63	1400.09
24	100	.008	.18	90.07	1201.54

TABLE III (continued)

TEST NO.	b_0	b_1	b_2	b_3	$\hat{\sigma}^2$
8	10.711	-2.28	-.529	-.779	.0625
9	10.67	-2.33	-.59	-.75	.0593
10	10.70	-2.39	-.65	-.74	.0562
11	12.44	-2.56	-.48	-.75	.0915
12	12.44	-2.56	-.48	-.76	.0802
16	11.54	-2.51	-.62	-.77	.0852
20	11.81	-2.58	-.64	-.73	.0732
24	11.46	-2.56	-.68	-.77	.0779

MAX. VARIANCE OF PREDICTED Ln(T): .0113

TABLE IV

MILLING TEST SIMULATOR: SECOND STRATEGY DATA

TEST No.	VEL.	fd	Rd	T.L.	FORCE
1	125	.005	.40	27.025	1367.284
2	175	.005	.20	23.066	824.102
3	125	.007	.20	37.640	1093.989
4	175	.007	.40	18.615	1716.174
5	150	.006	.30	27.066	1268.949
6	150	.006	.30	36.556	1553.382
7	150	.007	.14	56.852	788.585
8	100	.0046	.34	81.705	1578.23
9	150	.004	.22	58.074	847.774
10	195	.008	.10	16.54	591.034
11	190	.004	.18	21.429	712.436
12	120	.008	.14	82.890	918.123

TEST No.	b_0	b_1	b_2	b_3	σ^2
6	10.178	-1.242	.214	-.355	.0607
7	11.130	-1.225	.475	-.624	.0672
8	13.080	-2.122	-.034	-.608	.1020
12	11.074	-2.393	-.689	-.614	.1053

MAX. VARIANCE OF PREDICTED Ln(T): .0565

2.5.3 End Milling Analysis (continued)

these violations were minor. This illustrated the increased probability of violating the constraints when the range of the initial tests was large.

None of the remaining constrained tests in either strategy significantly violated the tool life constraints. The non-probabilistic constraint, however, was significantly violated. Violations of the force constraints probably would have damaged the cutter. The importance and usefulness of defining probabilistic constraints with a low risk of violation were thereby illustrated. Slight violations of the constraints were considered tolerable.

2.6 End Milling Experiments

2.6.1 Introduction

A series of end milling tests was conducted to determine the effect on tool wear and tool life of (a) in-process variations in feed and radial depth and (b) variation due to different Ti-6Al-4V microstructures. The primary objective of these tests was to determine how shop data on tool wear and tool life compared with that obtained in a laboratory.

During numerical control (NC) and adaptive control (AC) end milling cuts, the radial depth and feed are generally not constant. As the cutter goes around a corner which has been radiused by a larger diameter cutter in a previous cut, it encounters a sudden increase in the radial depth. There are also a number of NC cutter paths where it is advantageous to vary the radial depth systematically to obtain economic combinations of tool life and cutting rate. In AC cuts, as the cutter becomes dull or as a larger radial depth is encountered, the rise in cutting force signals a feedback response to slow down the feed rate. Thus both the radial depth and the feed will vary during a given AC cut.

For such cuts, there is presently no systematic procedure to develop mathematical models. Until now, almost all efforts have been directed toward the development of mathematical models when each of the machining variables such as speed, feed, etc., are held at a predetermined constant value for each individual test.

The series of tests conducted in this project revealed that the behavior of tool life is strongly "path dependent". That is, that tool wear and consequently tool life depend not only on the current level of each of the

variables, but also on the cummulative effect of the previous levels to which the cutter was exposed during a given cut. In the following, the data and results of these experiments are summarized. Shop floor observations of tool life during NC cuts on a production airframe part at the McDonnell Douglas Aircraft Company in St. Louis, MO are compared to the laboratory data on tool life generated using similar end mill cutters.

2.6.2 Test Equipment

A Cincinnati Cinova 80 vertical milling machine having infinitely variable speed and feed drives was used for the peripheral end milling tool life tests. The milling machine was equipped with a digital spindle speed readout and a digital wattmeter which displayed spindle motor power during the cut. See Figure 19.

The machine was also equipped with a spindle deflection sensor manufactured by the Macotech Corporation. The signals from this unit were fed into a Model 850 Sanborn recorder that produced a strip chart which after having been properly calibrated, indicated pounds force in the X or feed direction and in the Y or transverse direction and also gave the resultant force which was electronically calculated from the X and Y components.

2.6.3 Test Procedure

The following experimental procedure was adopted for conducting the peripheral end milling tool life tests on annealed Ti-6Al-4V titanium alloy. These tests were conducted using 3/4" and 1" diameter NAS end mills, and all cuts were taken in the climb mode. The cuts were taken on a previously machined workpiece of 4" x 3" rectangular cross section approximately 12" long clamped in a fixture mounted on the milling machine table as shown in Figure 20.

The cutting force was recorded continuously on the Sanborn strip chart during the cuts. The wattmeter reading was recorded at the start of the test and for each successive pass. After a predetermined number of passes, the total deflection of the tool, workpiece and machine system was measured by moving the rotating tool into the work until contact was made. The difference between the dial reading at contact and the dial setting during the cut was the deflection. The deflection was recorded in this manner at three axial depths, at the top of the

cut, in the middle and at the bottom end of the cut. The tool was then removed and the uniform and localized wear was measured and recorded. The test was continued until either localized wear reached .020" or excessive chipping occurred. Some tests were discontinued when there was no appreciable change in the uniform or localized wear after prolonged cutting.

2.6.4 3/4" Cutter Tests

Tool life tests were conducted with 3/4" diameter, 3" flute length, 4-flute NAS end mills on annealed Ti-6Al-4V. Various combinations of radial depth and feed rate were selected to give constant cutting rates representative of production practice as well as those reflecting the capability limits of the cutters.

The large length to diameter ratios of these end mills caused the tool deflection to be quite high; as a result, many of them failed by excessive chipping of the cutting edge. In some cases, the chipping was localized as is shown in Figure 21, while in other instances, the chipping took place all along the cutting edge as is shown in Figure 22. End mills that did not have the tendency to chip were run at the same combinations of radial depth and feed rate for two hours with only a minimal amount of wear, not exceeding a .003" wearland at any of the conditions tested.

Cutters run at cutting rates less than .43 cubic inches per minute did not chip during the two hour tests. Figures 23 and 24 show the feed and radial depth combinations that did not cause chipping of the cutter.

In Figures 25 through 38, the uniform and localized wear, the total deflection and the resultant cutting force are plotted against cutting time. Note that the deflection and cutting force closely follow the uniform wear. The localized wear does not affect the cutting force and deflection until it approaches the tool life end point or the point of catastrophic failure. The rates of change of both the cutting force and deflection are good indications of the uniform wear and therefore, can be used for predicting tool life providing conditions are chosen so that uniform wear criteria are applicable. However, when either localized wear or excessive chipping occurs, the cutting force and deflection signals cannot be used to predict the tool life end point. This is often the case when end milling titanium.

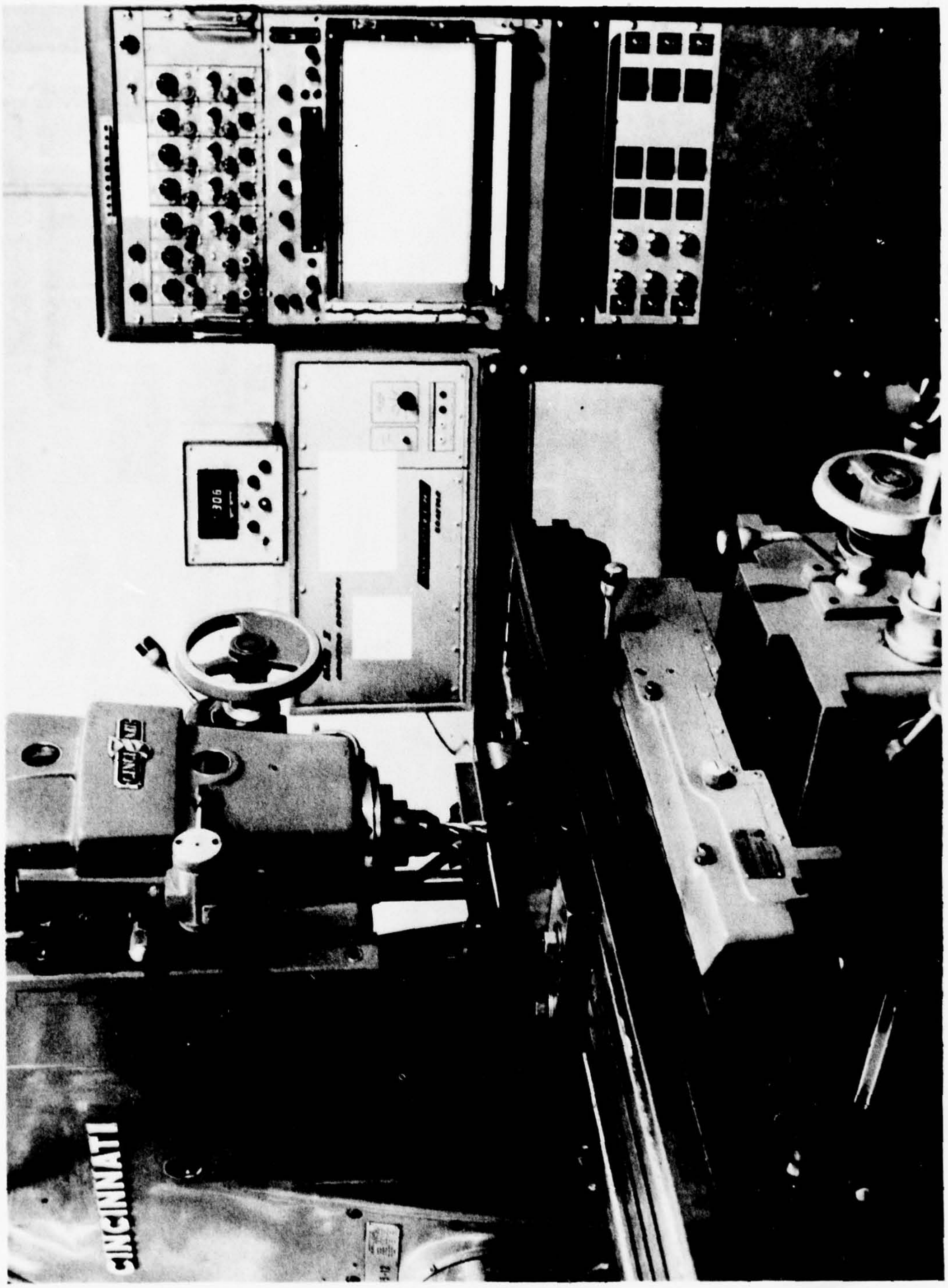


Figure 19 - CINCINNATI CINOVA 80 VERTICAL MILLING MACHINE EQUIPPED WITH A 7-1/2 HP VARIABLE SPEED DRIVE AND ALSO FULLY INSTRUMENTED FOR MEASURING CUTTER FORCES, CUTTER DEFLECTION, AND HORSEPOWER

Plate: 6489

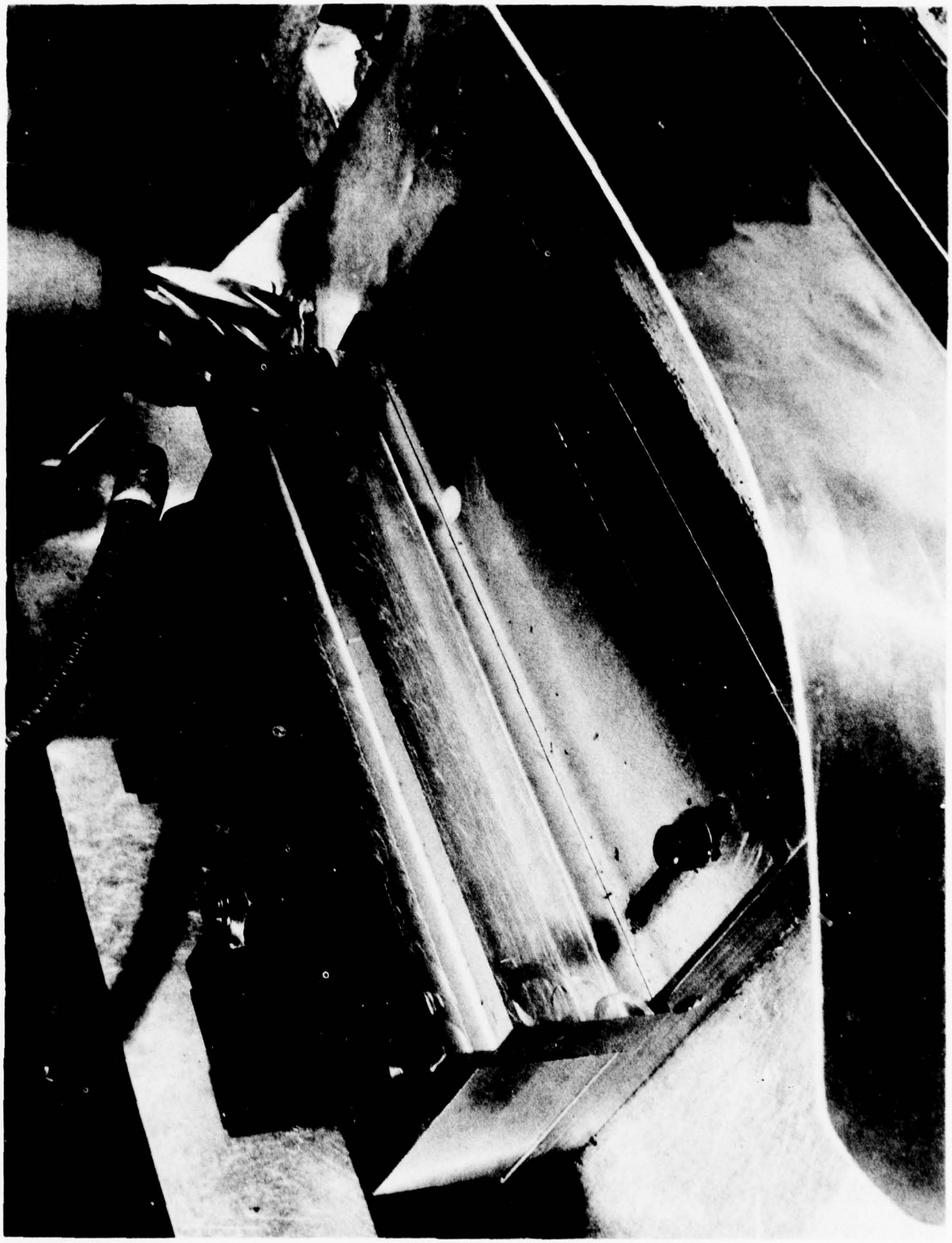


Figure 20 - PERIPHERAL END MILLING TEST SETUP

Plate: 6176

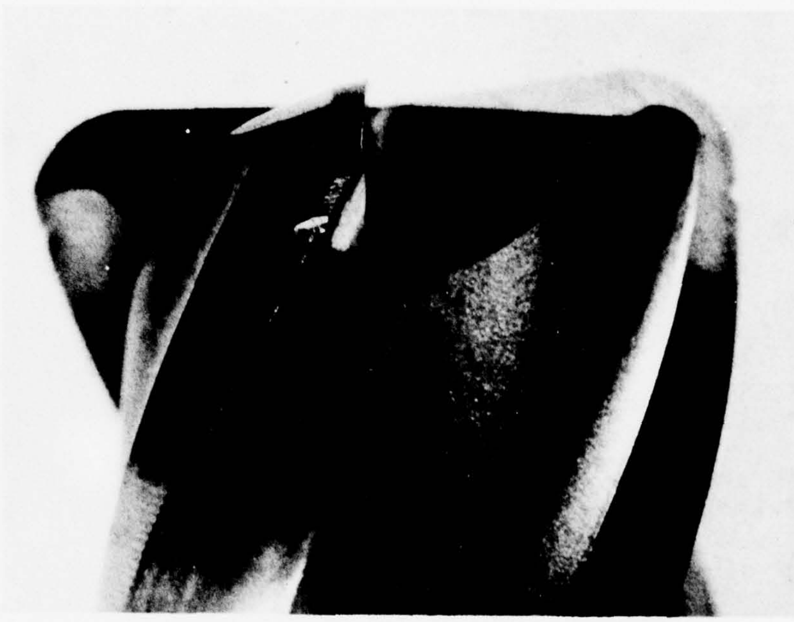


FIGURE 21 - END MILL WITH LOCALIZED CHIPPING

FIGURE 22 - END MILL WITH CHIPPING ALL ALONG CUTTING EDGE

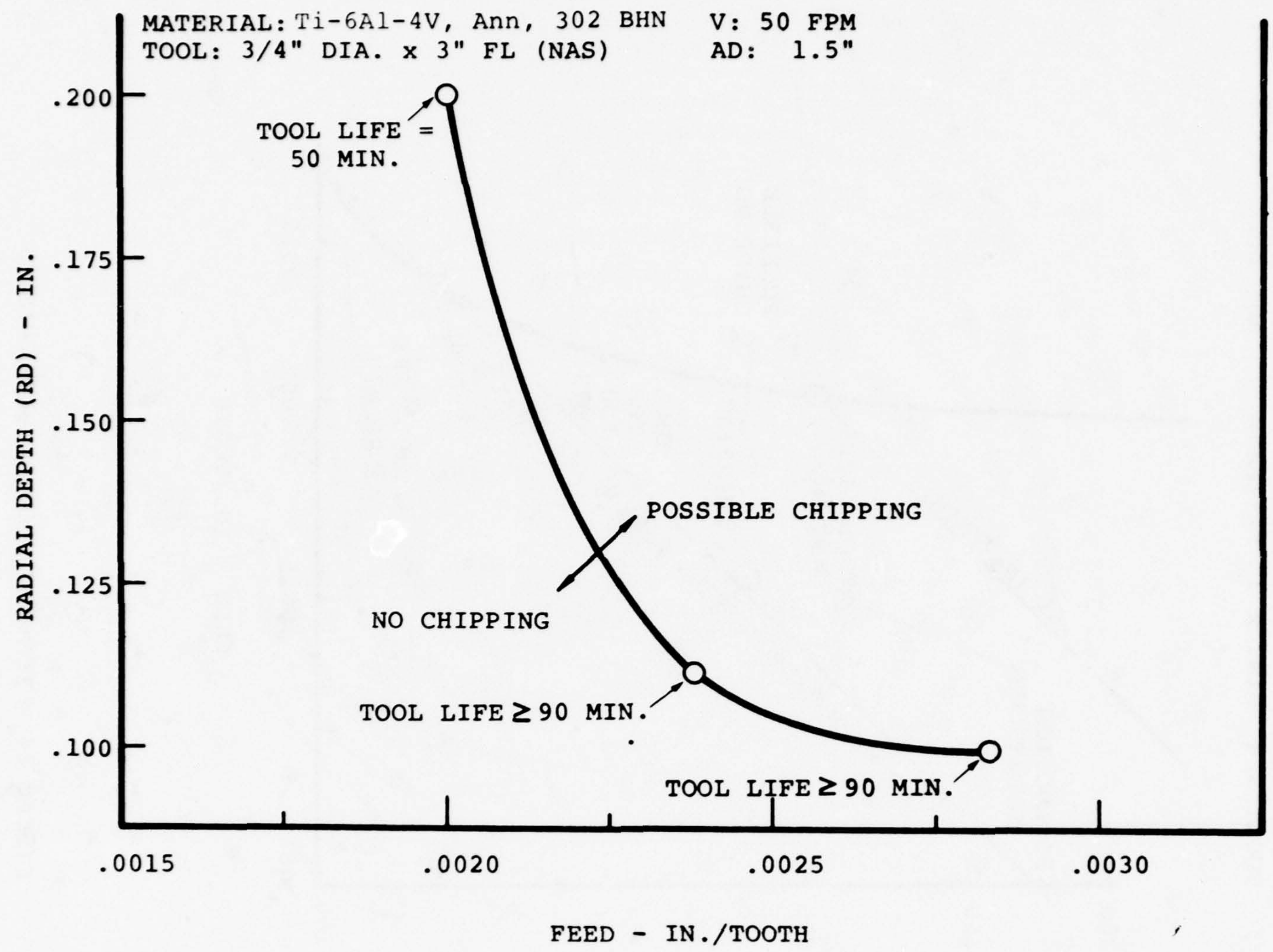


Figure 23 - FEED AND RADIAL DEPTH COMBINATIONS THAT PRODUCED NO TOOL CHIPPING

MATERIAL: Ti-6Al-4V, Ann, 302 BHN   V: 50 FPM
TOOL: 3/4" DIA. x 3" FL (NAS)   AD: 1.5"

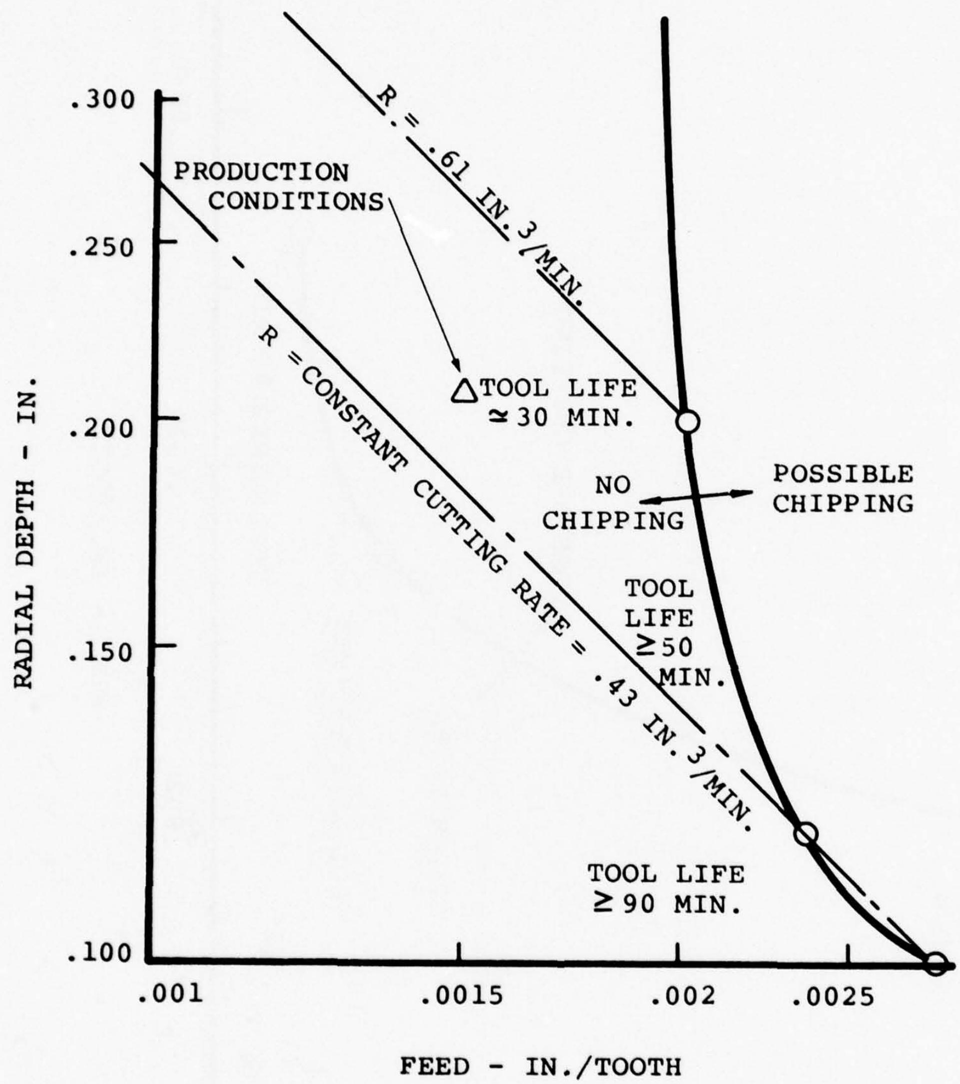


FIGURE 24 - LOG-LOG PLOT OF DATA POINTS

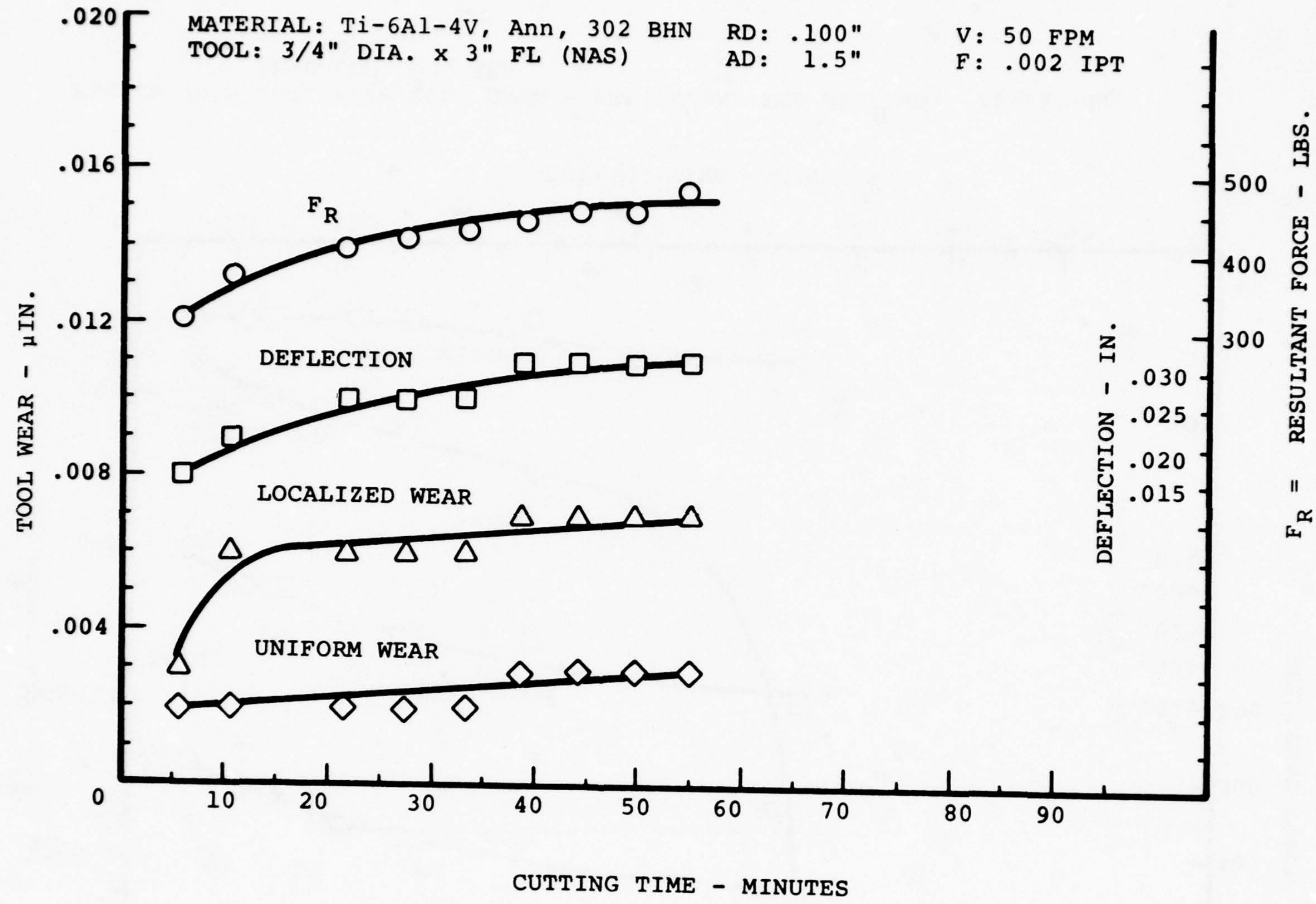


Figure 25 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNELAED, 302 BHN

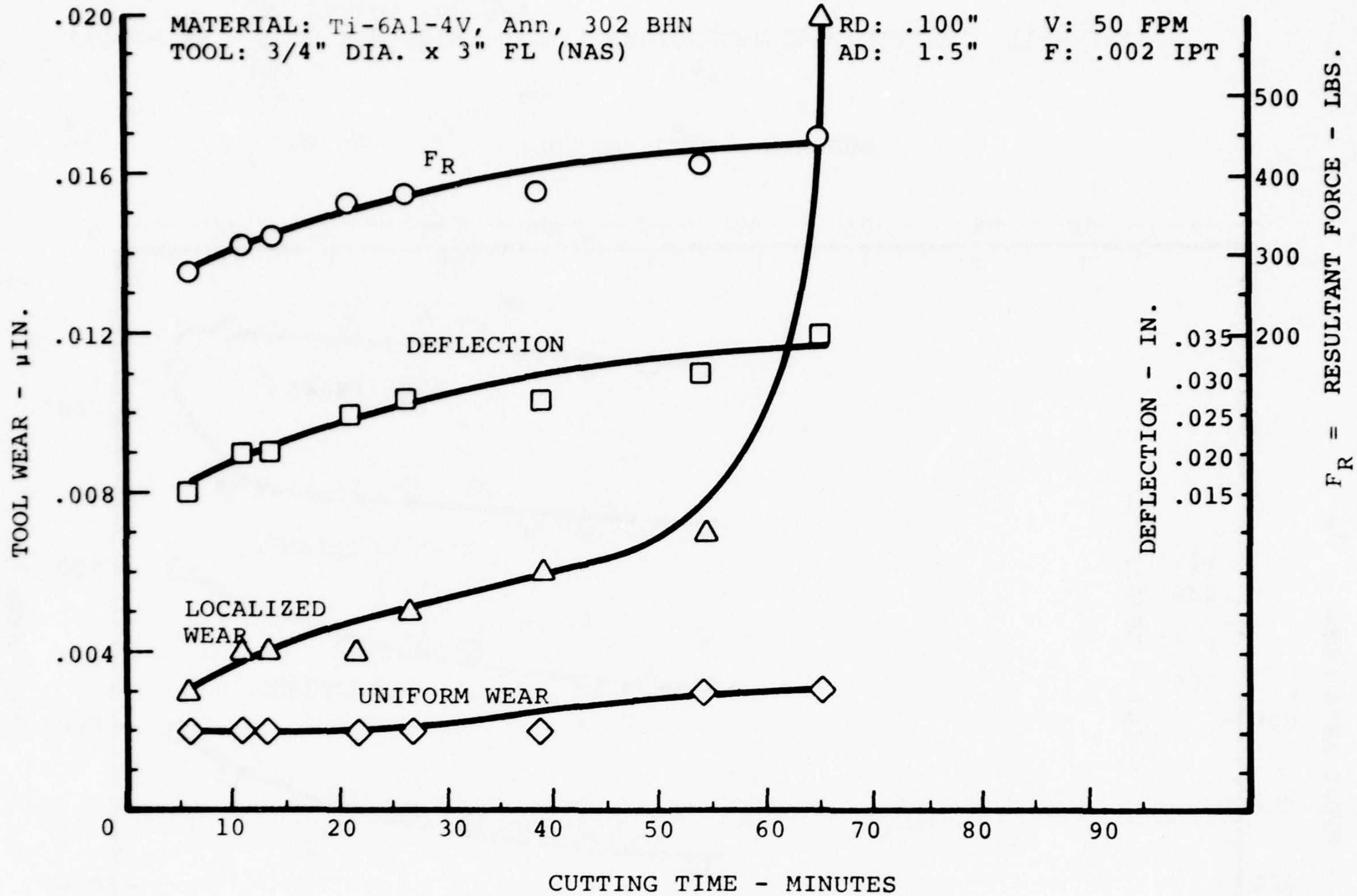


Figure 26 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

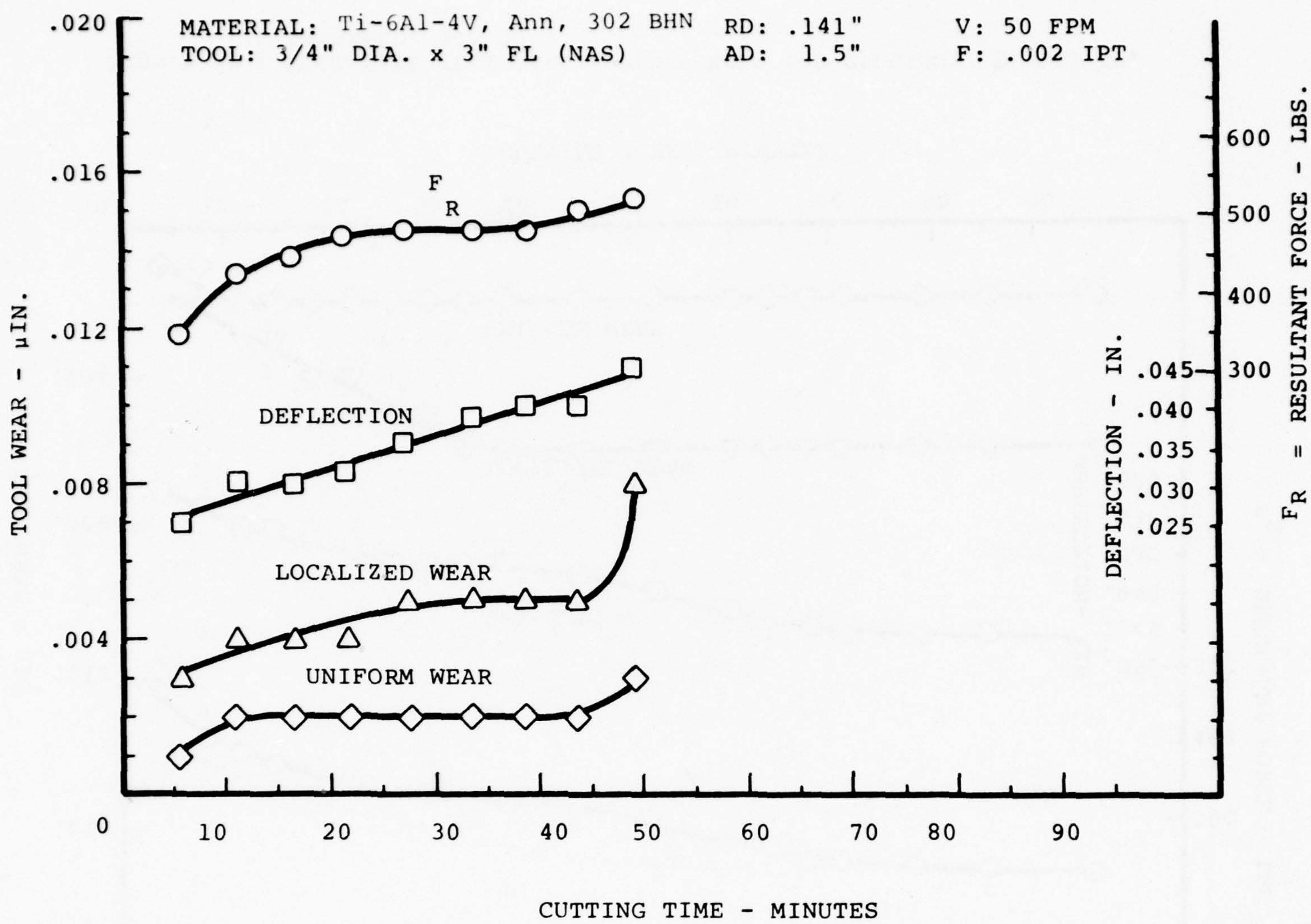


Figure 27 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

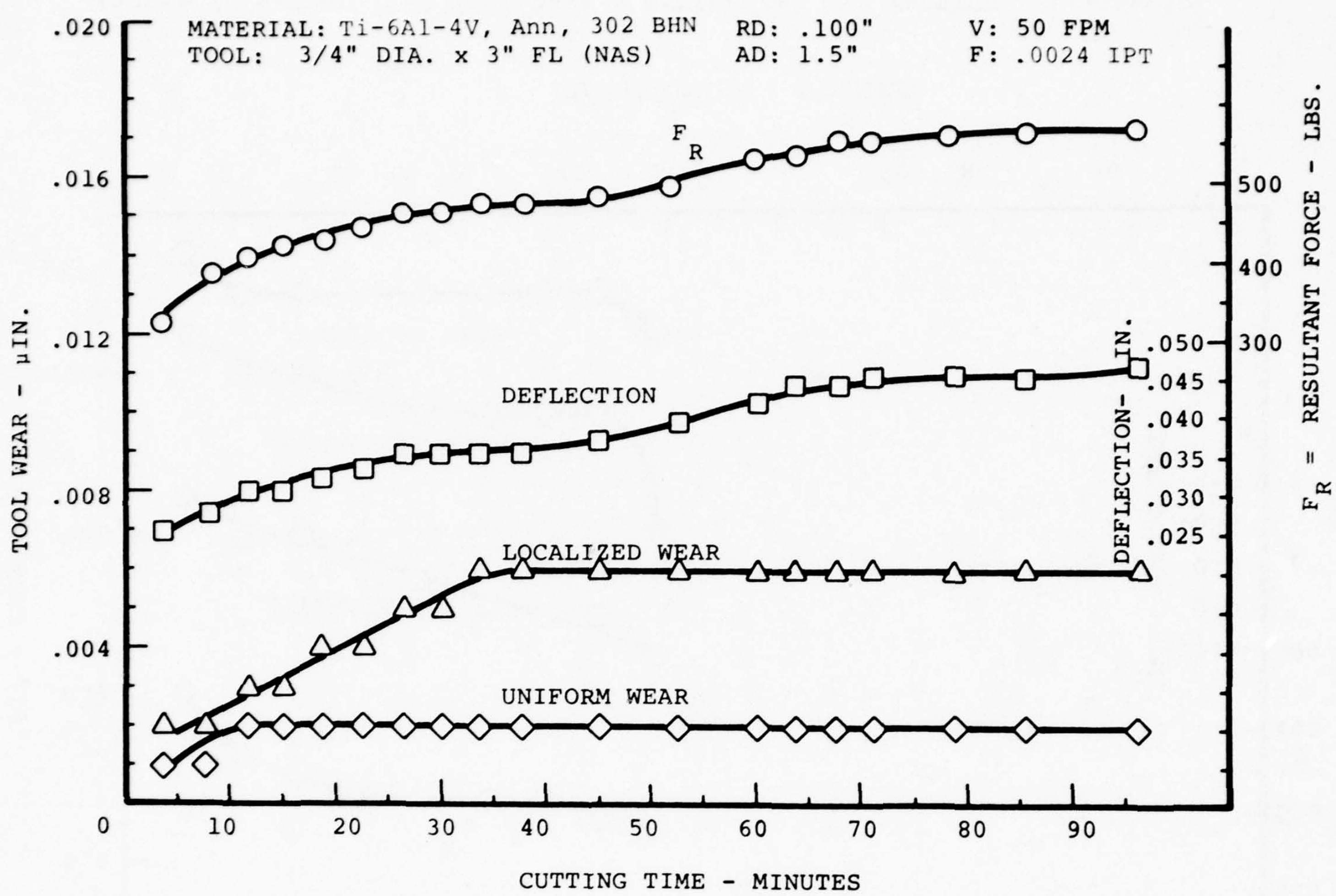


Figure 28 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

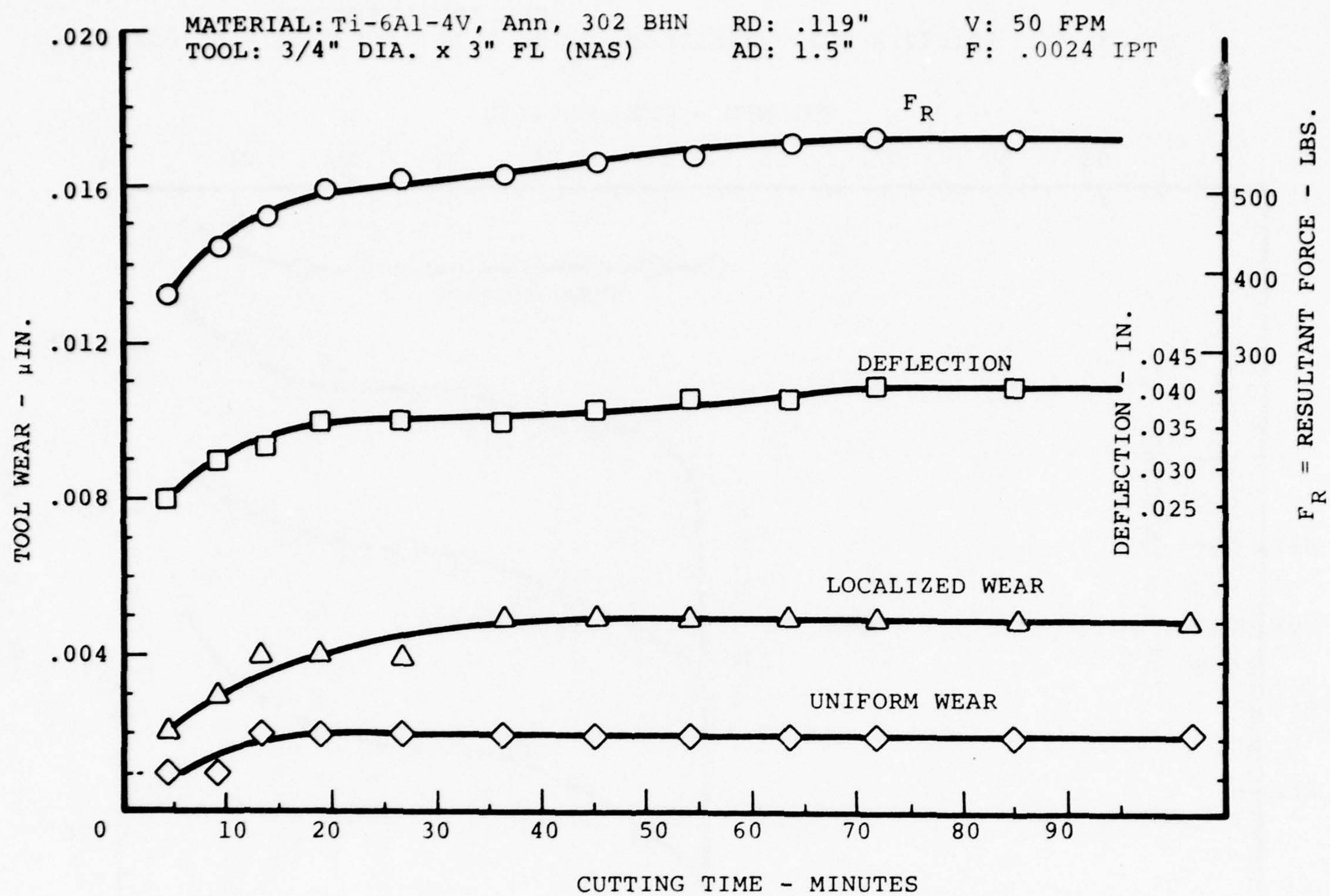


Figure 29 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

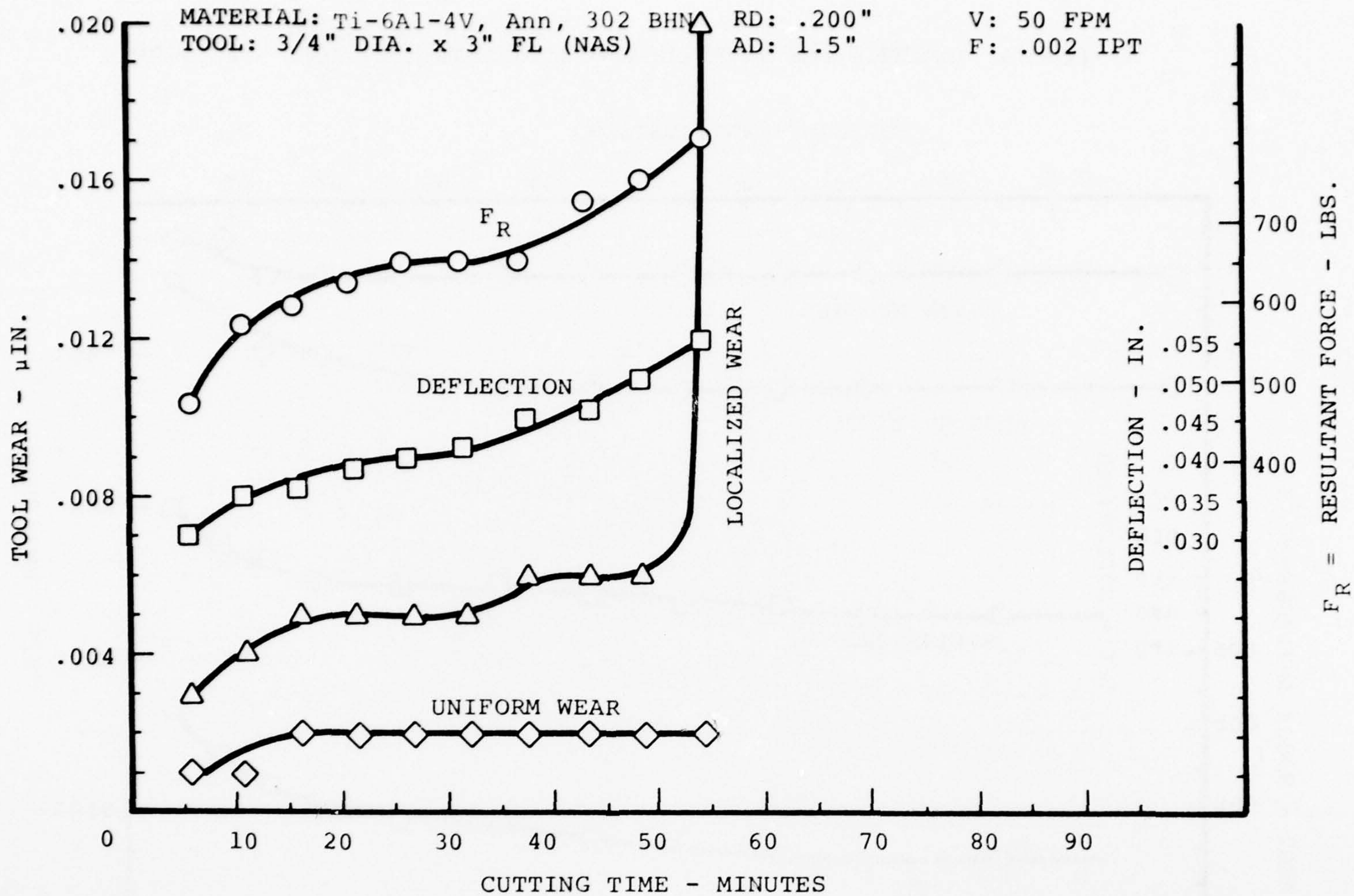


Figure 30 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

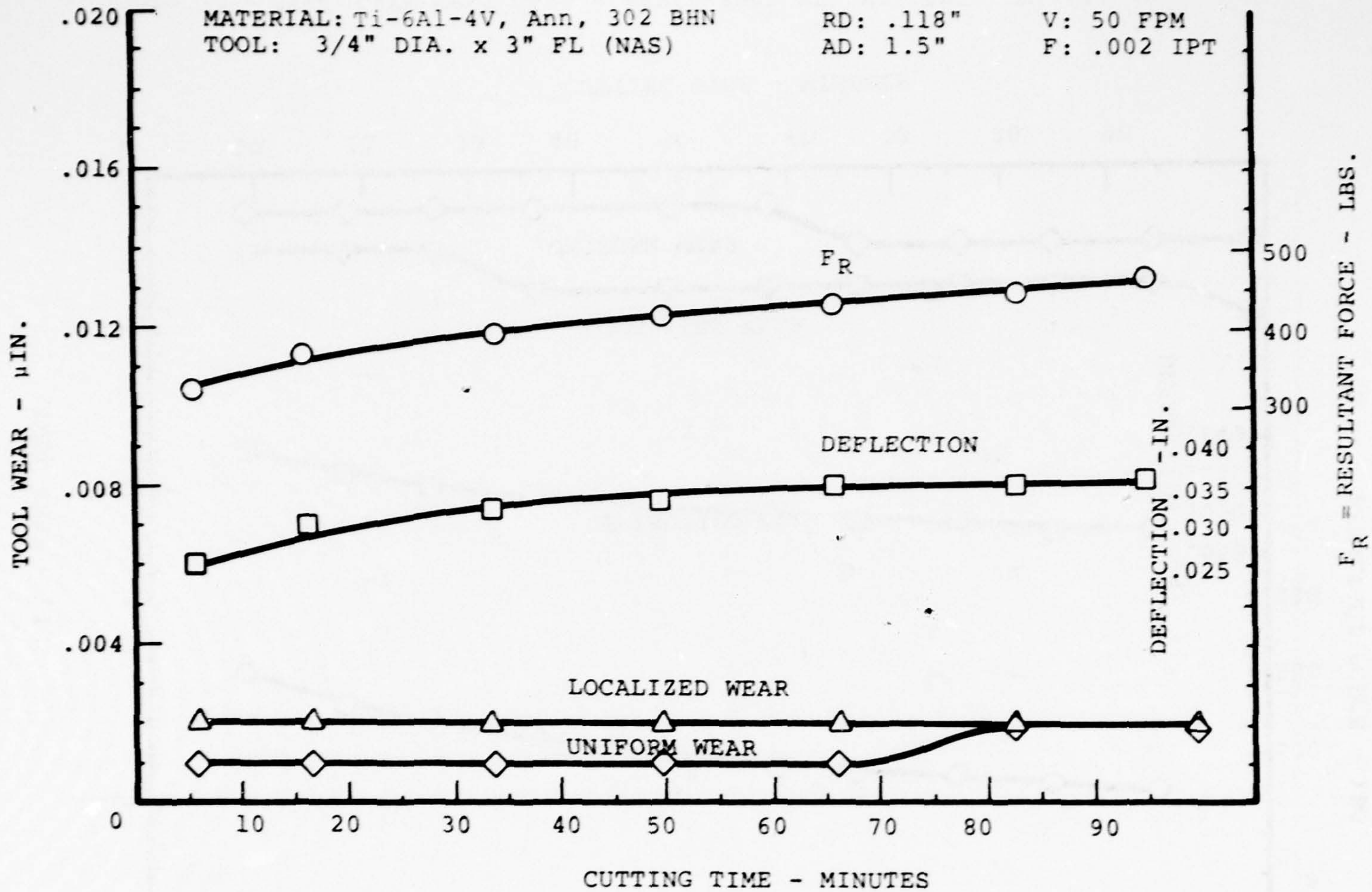


Figure 31 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

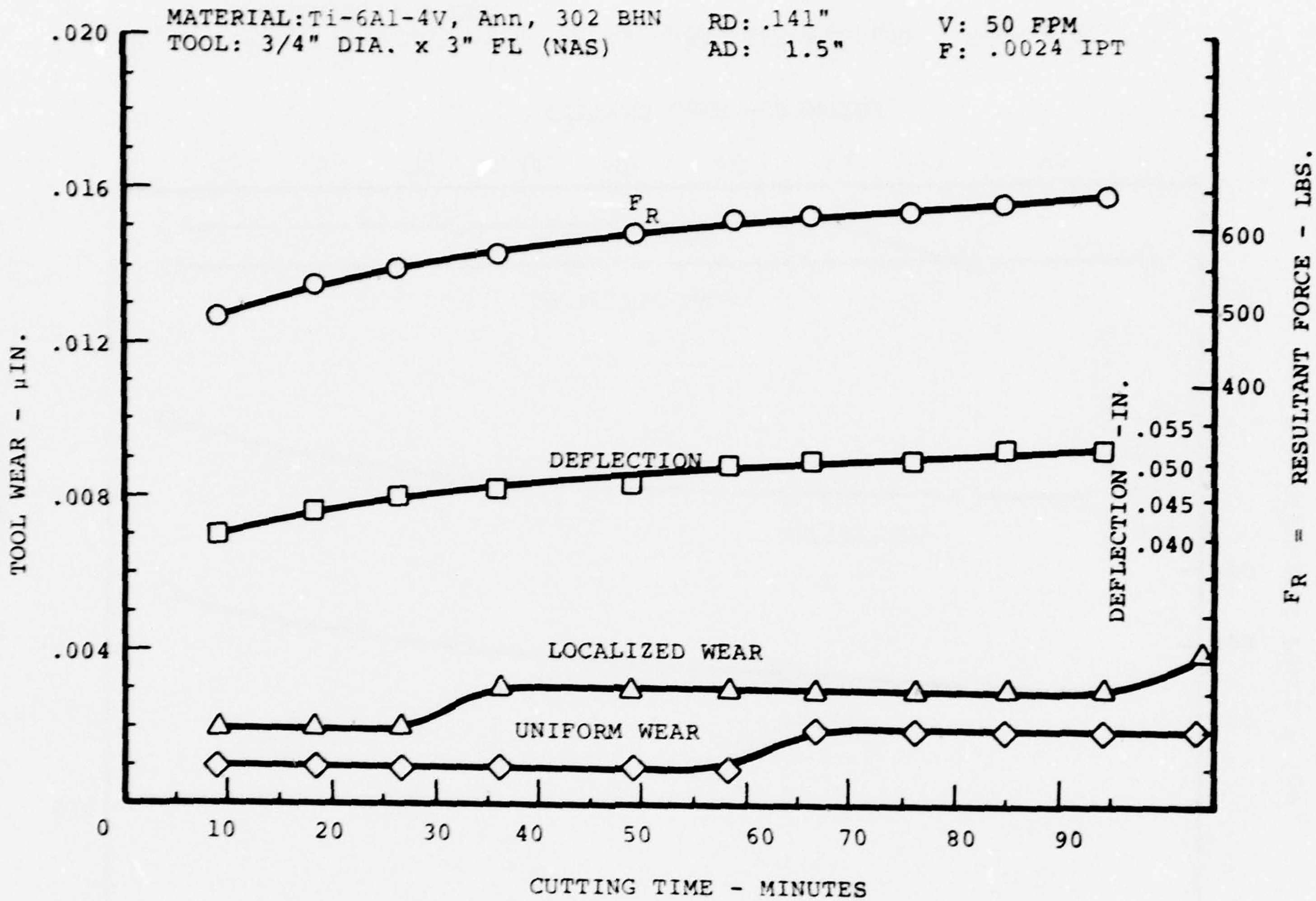


Figure 32 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

MATERIAL: Ti-6Al-4V, Ann, 302 BHN RD:.141" V: 50 FPM
TOOL: 3/4" DIA. x 3" FL (NAS) AD: 1.5" F: .002 IPT

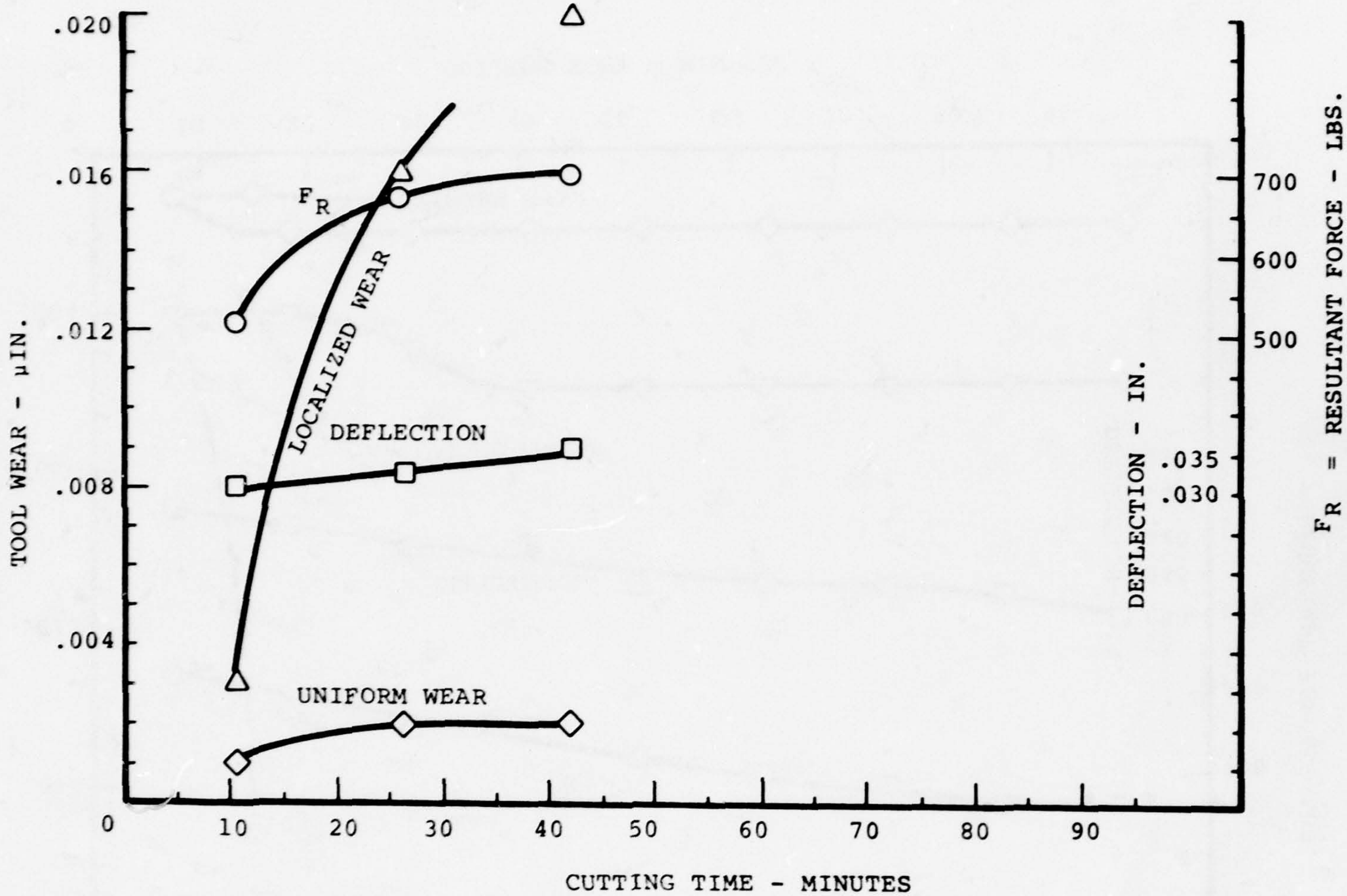


Figure 33 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

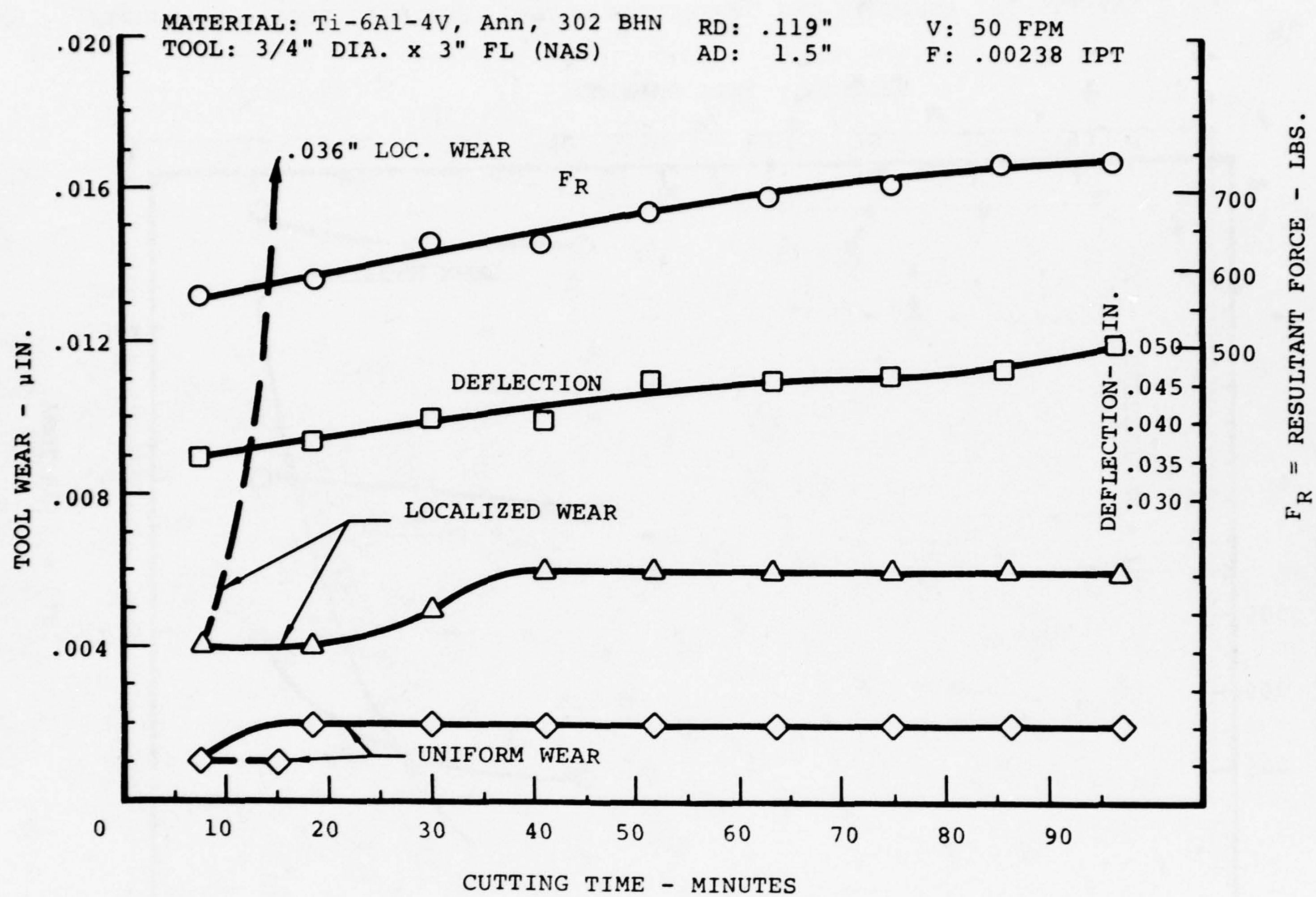


Figure 34 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

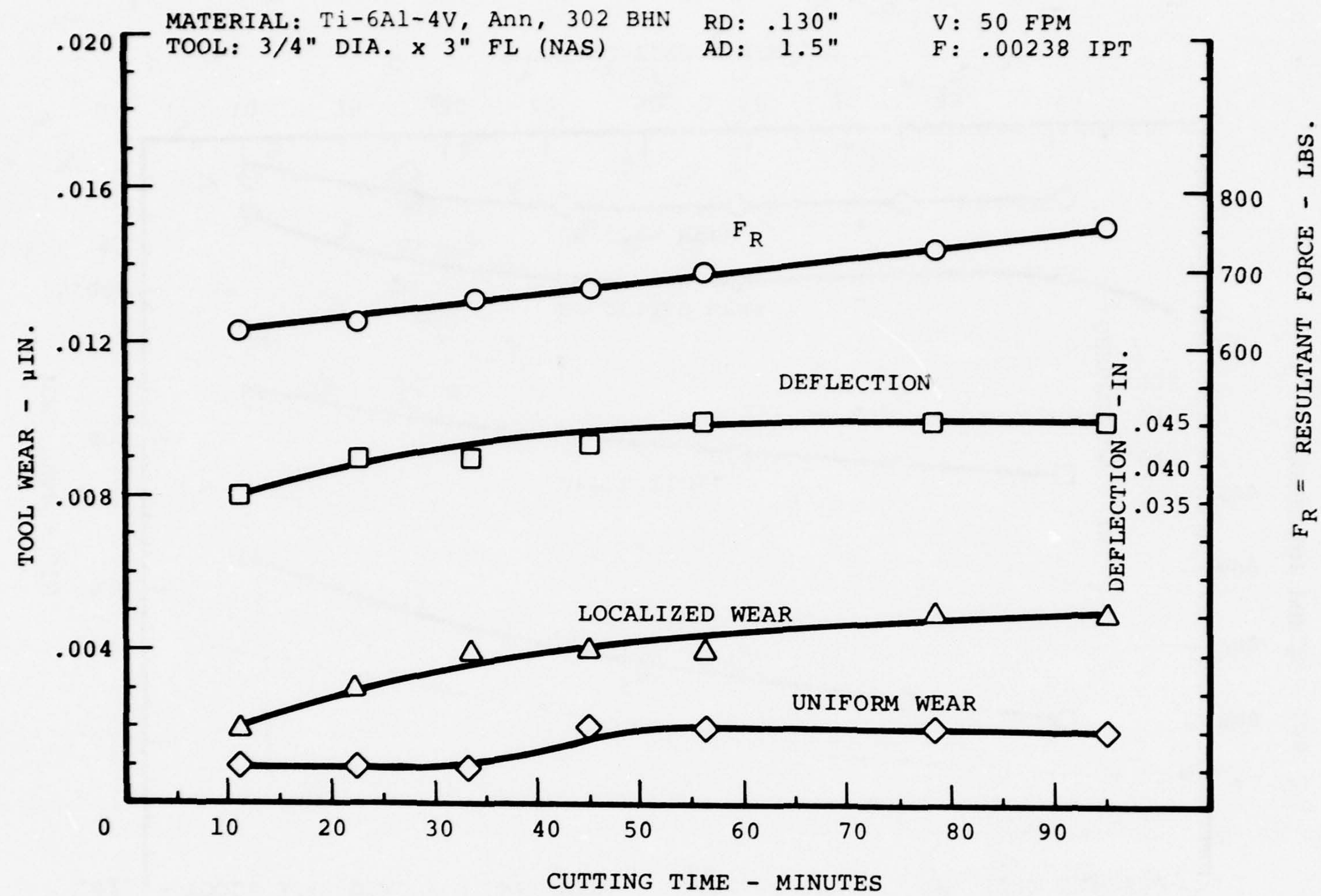


Figure 35 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

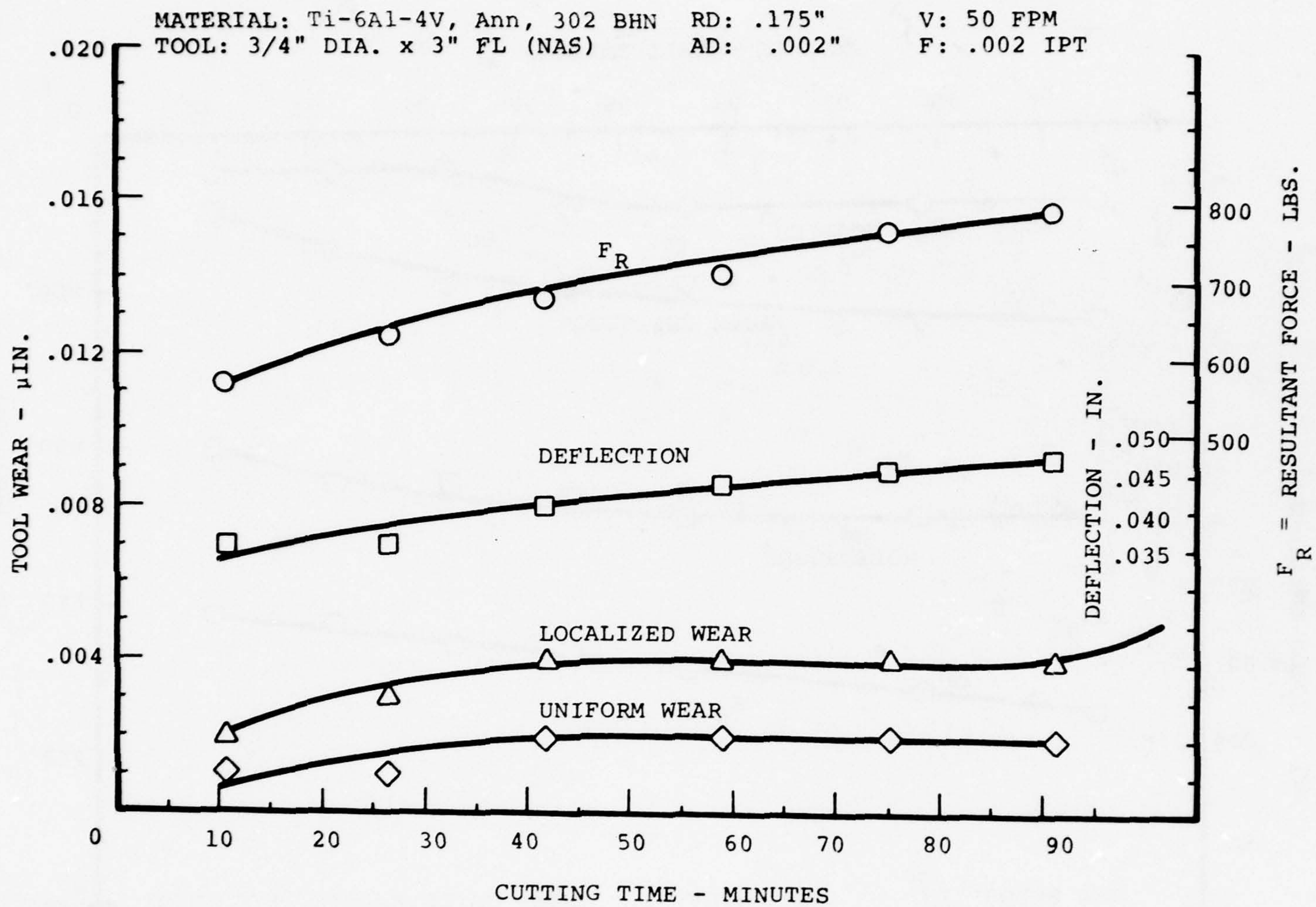


Figure 36 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

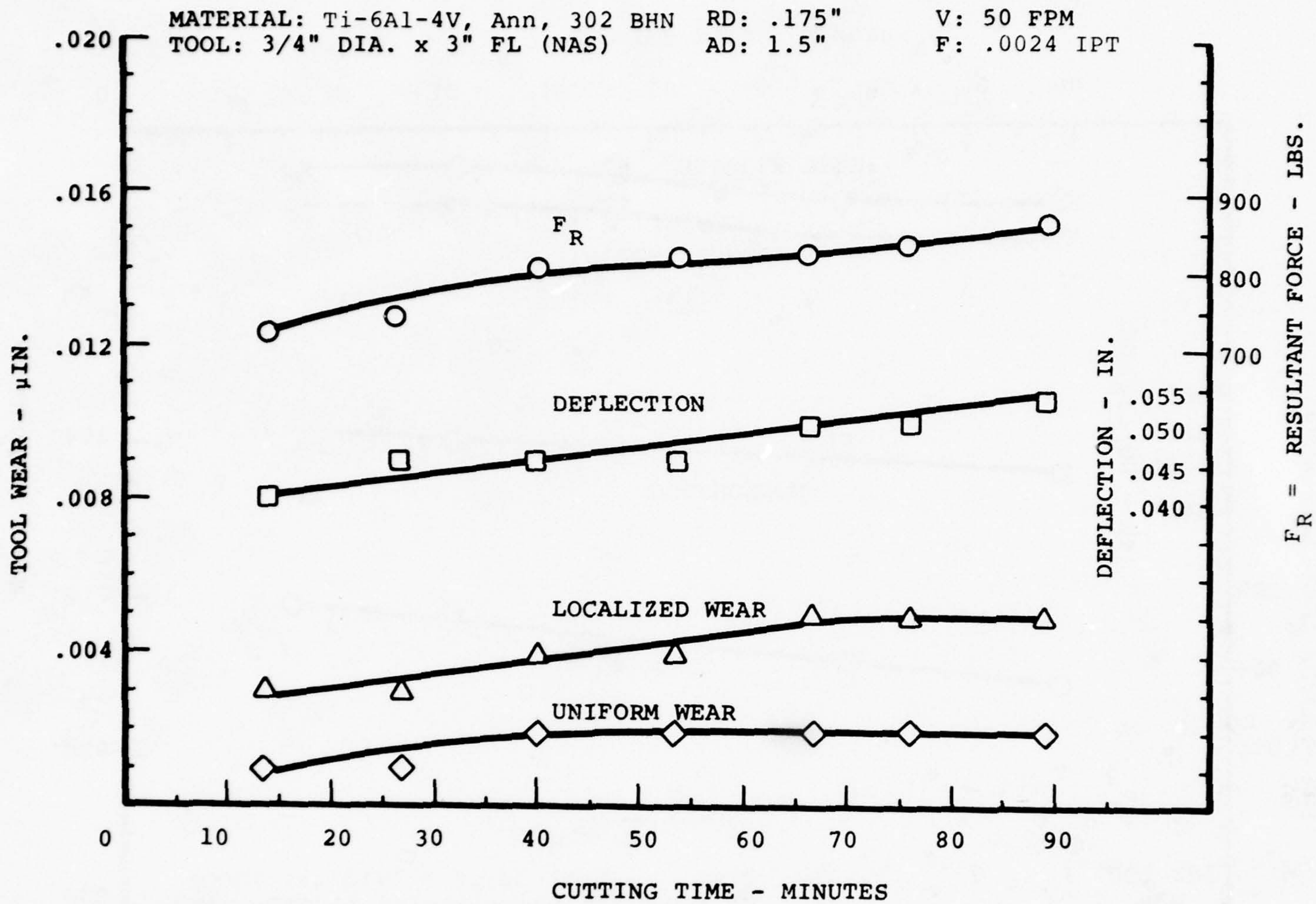


Figure 37 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

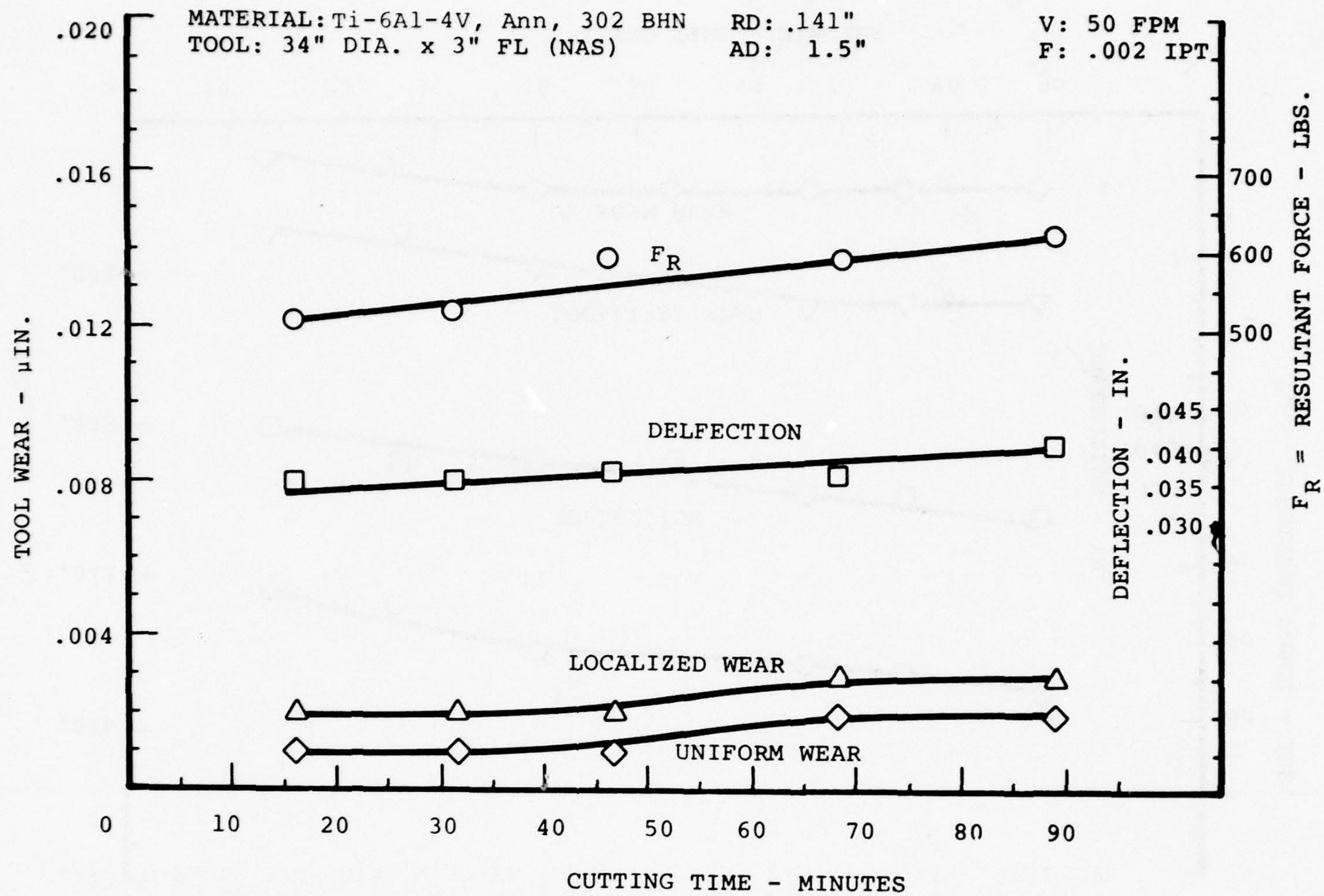


Figure 38 - TOOL LIFE TEST DATA - PERIPHERAL END MILLING: Ti-6Al-4V, ANNEALED, 302 BHN

2.6.5 Correlation With Production Data

A group of Ti-6Al-4V production airframe parts were followed through various NC end milling cuts on the production floor at the McDonnell Douglas Aircraft Company, St. Louis, MO. The NC cutter path on the part was analyzed to establish the length of cut as well as the average cutting rate (cu. in./min.). During the production floor observations, a record of tool wear, tool change frequency and operating conditions was maintained. It was observed that the operator examined the cutter for signs of wear and chipping during every cutter stop (approximately 30 minutes) and changed the cutters at the slightest sign of localized chipping. This was generally determined by running a fingernail across the cutting edge. Observations of the worn and replaced production cutters using a microscope established that localized wear or chipping of about 0.003" to 0.006" or more was detected by this method. In comparison, laboratory tests on similar cutters found that maximum localized wear of about 0.008" could be tolerated by the cutters without endangering catastrophic failure. In this light, the production cutter change practice was found to be somewhat conservative.

The correlation between the production conditions and the laboratory established performance limits for the cutters is shown in Figure 24. The feed and average radial depth on the production part show that the tool change practice of approximately 30 minutes is also conservative. The performance limits of the cutter could be safely reached by increasing both the feed, up to about 0.002 ipt, and the tool change time, up to about 50 minutes. Since the production conditions were within these described by the laboratory established performance limits, the results of the production observations compared favorably with those of the laboratory tests.

2.6.6 End Milling Tests With Variable Radial Depths and Feeds

Since in actual production it is not always possible to maintain constant radial depths and feed rates, tool life tests were performed on Ti-6Al-4V using variable radial depths and feed rates in order to establish a correlation between production and test data using constant radial depths and feeds.

Two methods of conducting variable radial depth tests were used. In the first method, the workpiece was mounted at an angle to the milling machine table giving a uniformly varying radial depth across the workpiece. The workpiece was then repositioned after each pass to maintain the same variation in radial depth. The second method, which produced similar results, consisted of taking straight cuts across the workpiece and changing the radial depth for each pass. The first pass was taken at the smallest radial depth, the second at the mean depth and the third at the greatest depth. This sequence of passes was then repeated until the tool life end point was reached.

The method just described was also used to conduct the variable feed tests. When the feed rate was varied from .005 to .007 ipt while the radial depth was maintained at .250", the end mill wear increased rapidly until it failed by chipping in five minutes. When the radial depth was varied between .150" and .350" while the feed rate was maintained at .006 ipt, the wear was not as rapid, but it failed by chipping in 14 minutes. Using constant conditions of .250" radial depth and a feed rate of .006 ipt, the wear rate was still less, .005" uniform and .007" localized after 33 minutes of cutting. (See Figure 39).

Tests were conducted to determine the constant conditions that would give the same tool life as the variable conditions. Figure 40 shows that when a constant radial depth of .250" was used, the uniform wear was nearly the same as when the radial depth was varied between .100" and .300". This indicates that the constant conditions chosen should be at the upper end of the variable range rather than selecting an average value as was done initially.

One of the most common instances of variable radial depths and feed rates occurs when finish machining a pocket on an NC milling machine. Tests were performed to simulate the effects of this cornering.

It was assumed that a 2" diameter cutter was used for roughing and a 1" diameter cutter was used for finishing. The workpiece was premachined to such a shape as to simulate the variation in radial depth and feed rate that is experienced during a uniform deceleration of the cutter into a corner. The radial depths were calculated at equal increments of table travel in order to maintain the same cutting rate at a constant feed rate as would be experienced in actual cornering with deceleration. These points were then plotted to obtain the shape of the premachined workpiece shown in Figure 41.

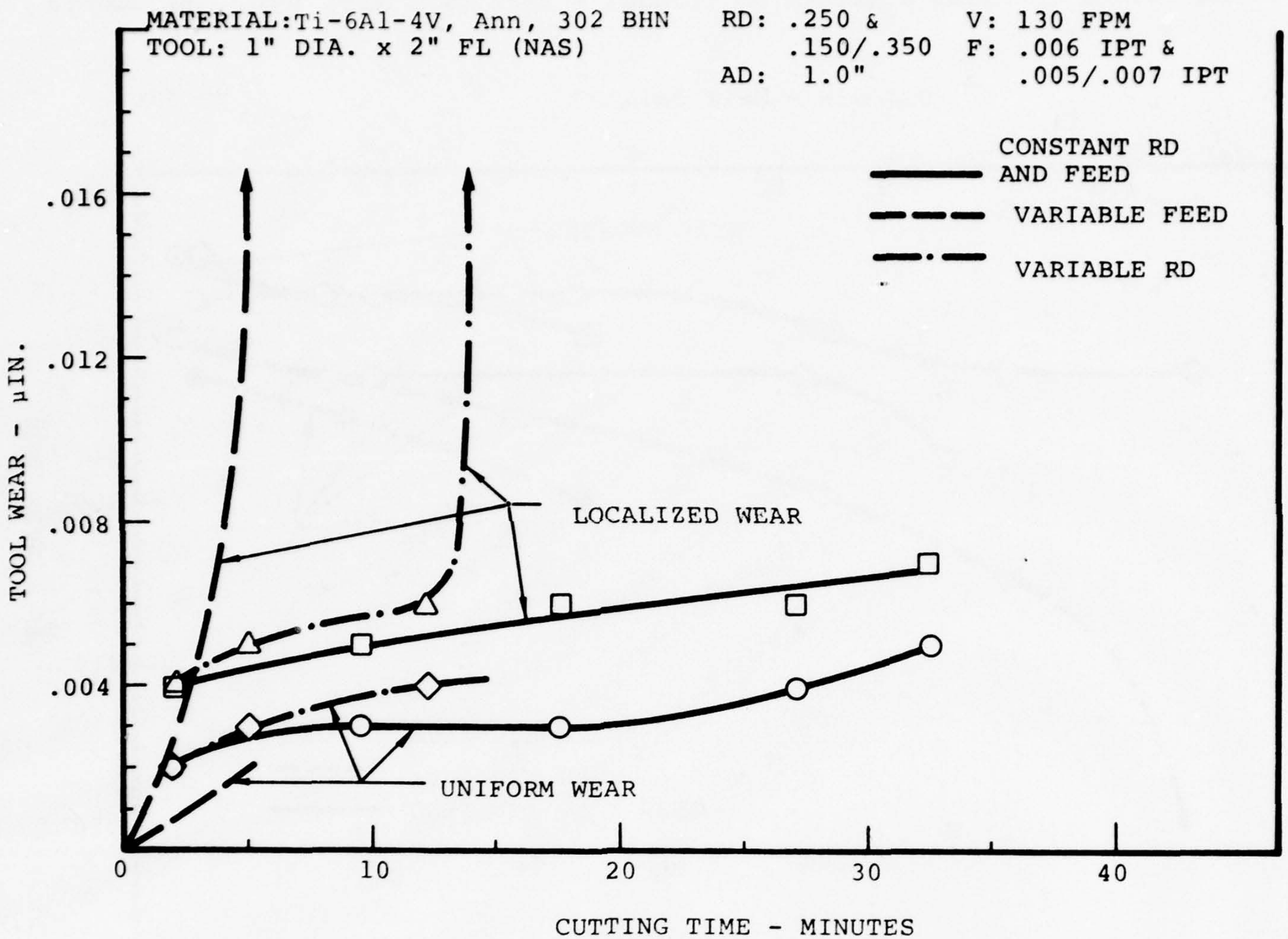


Figure 39 - TOOL LIFE TEST DATA - EFFECTS OF VARIABLE FEED AND RADIAL DEPTH

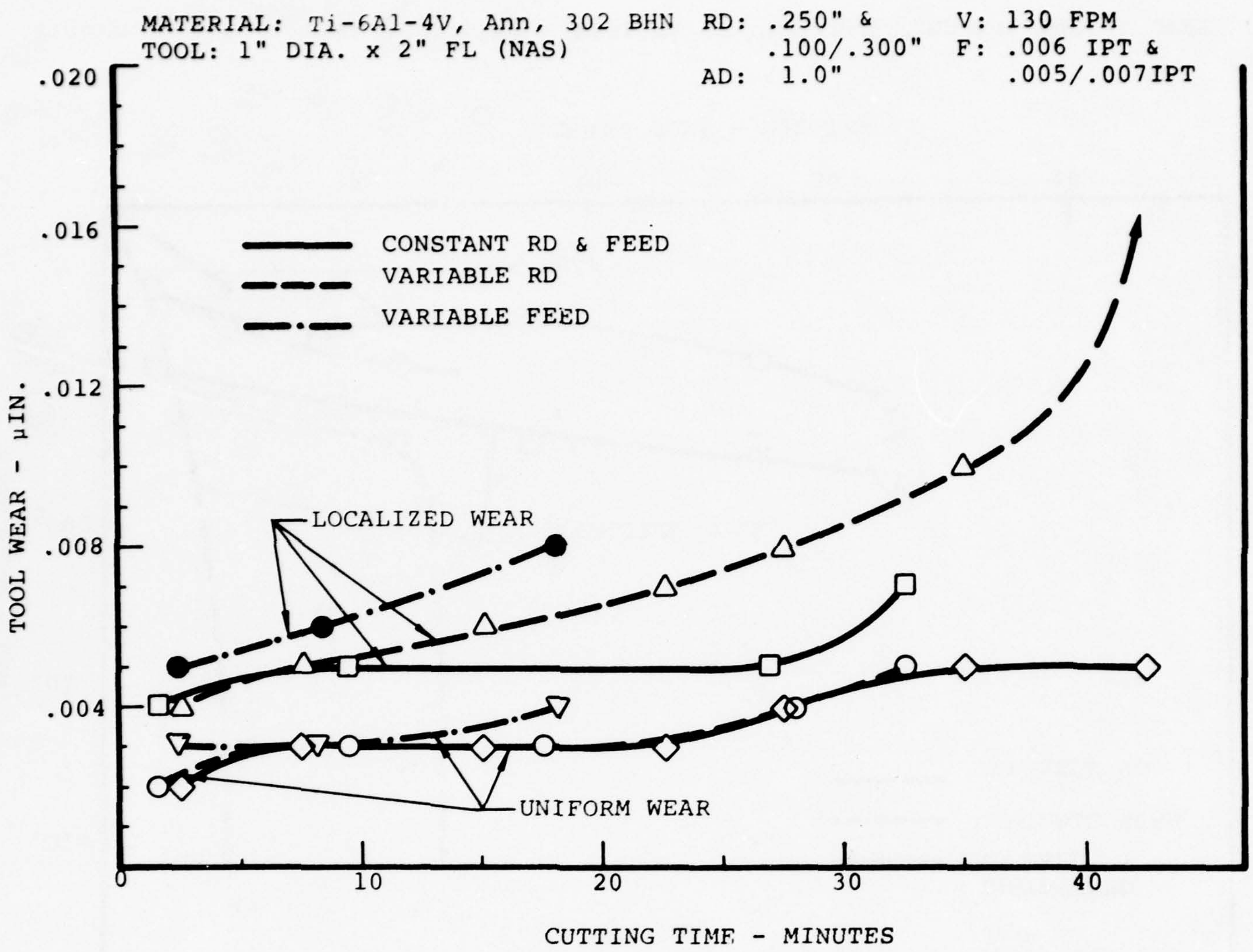


Figure 40 - TOOL LIFE TEST DATA - EFFECTS OF VARIABLE FEED AND RADIAL DEPTH

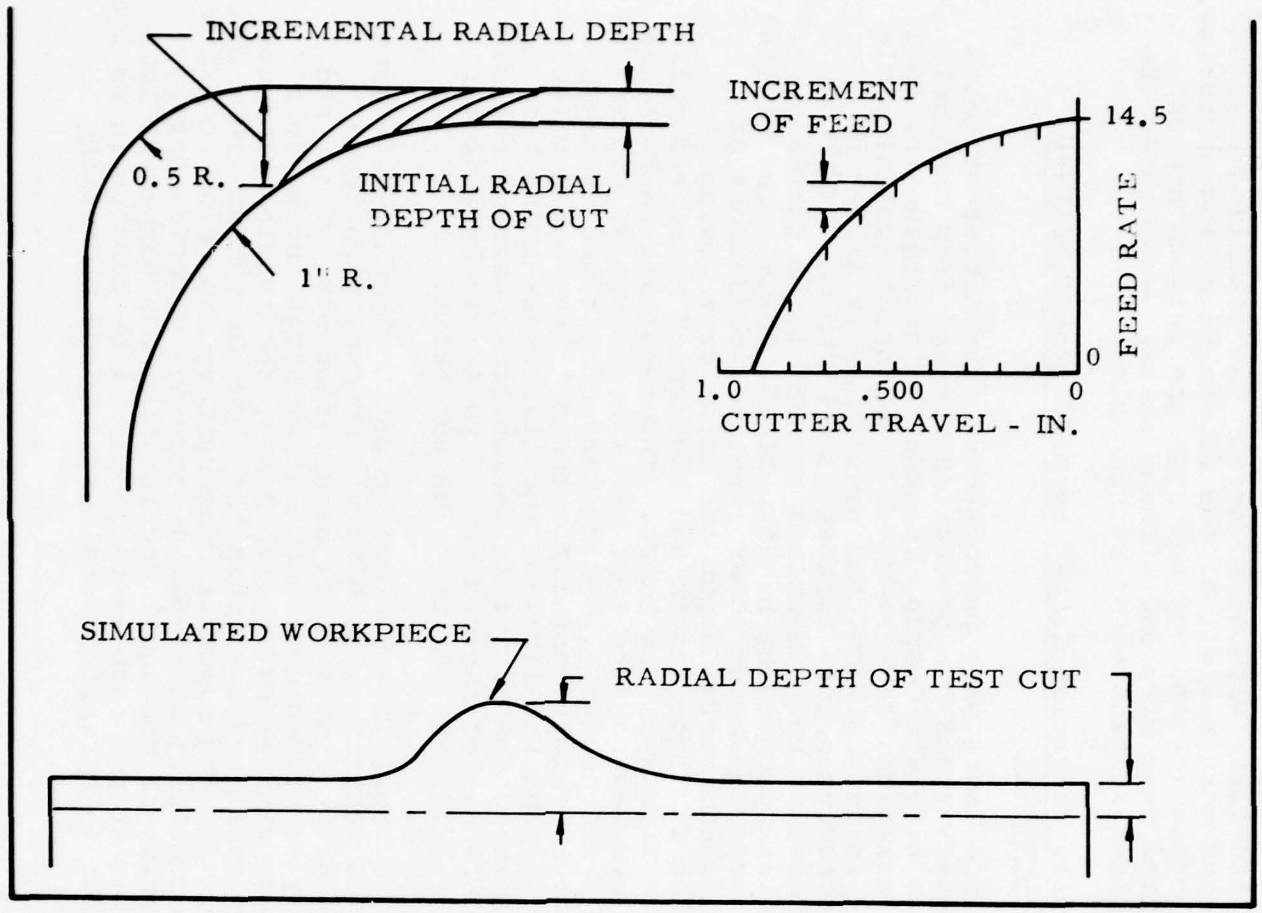


Figure 41 - DEVELOPMENT OF SIMULATED WORKPIECE FOR CORNERING TESTS

Figure 42 shows the results of these simulated cornering tests and tests without corners. The localized wear increased more rapidly at the beginning during cornering, but it then leveled out and both the uniform and the localized wear with and without corners was nearly the same after 80 minutes of cutting time.

2.6.7 Tool Life Variation Caused by Different Ti-6Al-4V Microstructures

Tool life tests were performed on four different heats of Ti-6Al-4V and one production forging from McDonnell Douglas Aircraft Company in order to determine the tool life variation. These materials, although nominally Ti-6Al-4V in composition, had significantly different microstructures (see Figures 43, 44 and 45). This was considered to be primarily a result of the thermal-mechanical processing history of the heats. End milling tests were conducted under identical conditions of speed, feed, radial depth and axial depth using 1" diameter 2" flute length NAS high speed steel end mill cutters from a single batch. The resulting uniform and localized wear on the four heats are shown in Figures 46 and 47, respectively. As evidenced by these figures, there were significant differences in the uniform tool wear rate and the level of localized wear among the four heats. The tool life variability observed during the tests was of the order of 3 to 4 fold between the worst (#7773) and the best (#8009) heats.

A similar tool life comparison of the Ti-6Al-4V forging from McDonnell Douglas Aircraft Company with the Ti-6Al-4V block from heat #4 used during most of the end milling experiments showed that although the uniform wear was similar on the two heats, the forging produced higher localized wear than the block (see Figure 48). This could account for the somewhat conservative machining conditions for end milling of Ti-6Al-4V forgings observed during production at McDonnell Douglas Aircraft Company. Tool life variations such as these should be further investigated in order to establish metallurgical and processing causes.

Effects of Cutter and Part Rigidity

In calculating the force from the Sanborn readings, it was assumed that the force was acting at the center of the axial depth. Figure 49 illustrates three conditions which might exist during a cut.

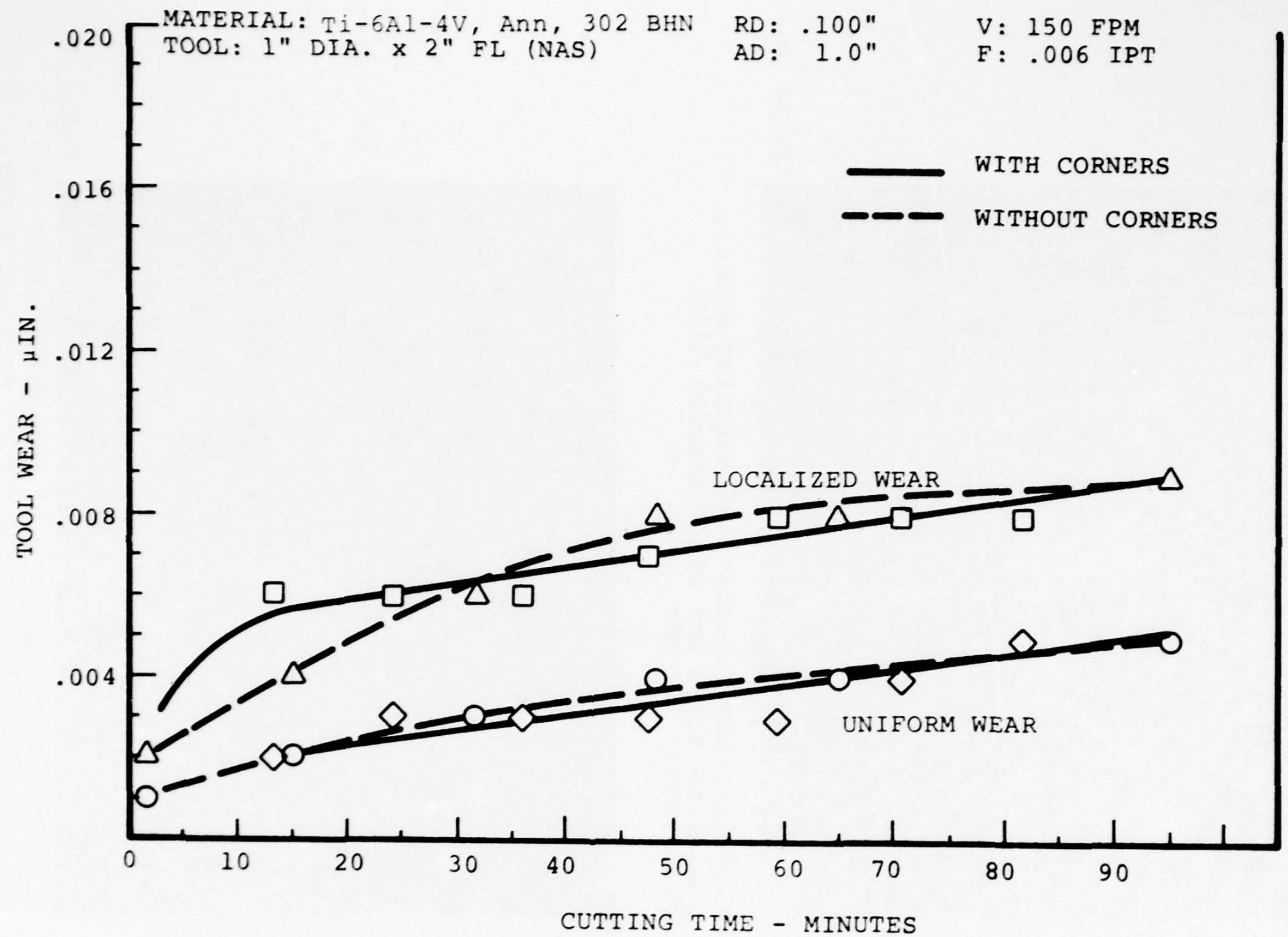


Figure 42 - TOOL LIFE TEST DATA - EFFECT OF CORNERING

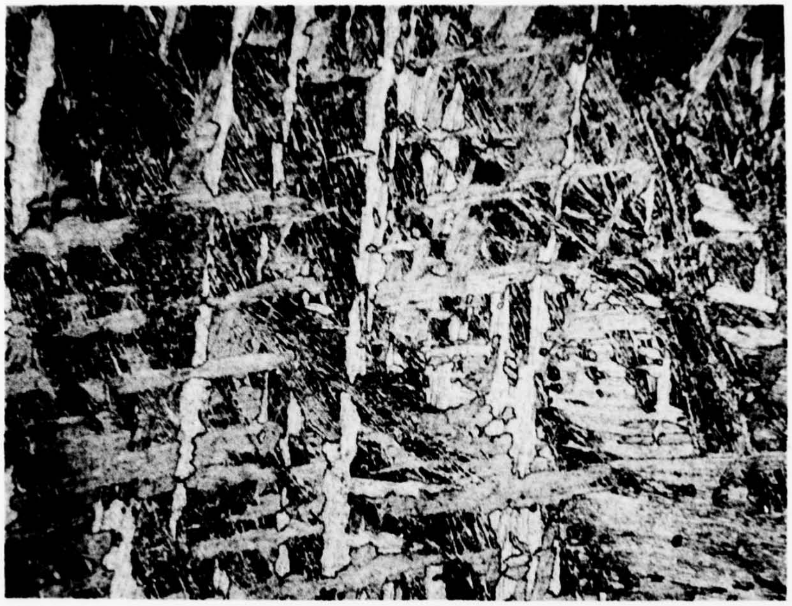


Plate No. 21040

Microstructure consists of acicular alpha, platelike alpha and intergranular beta. Heat #7773, 321 BHN

Plate No. 21040

Microstructure consists of elongated alpha and transferred beta containing acicular alpha. Heat #4, 302 BHN.

FIGURE 43 - COMPARISON OF MICROSTRUCTURES OF DIFFERENT HEATS OF ANNEALED Ti-6Al-4V

Mag: 250X

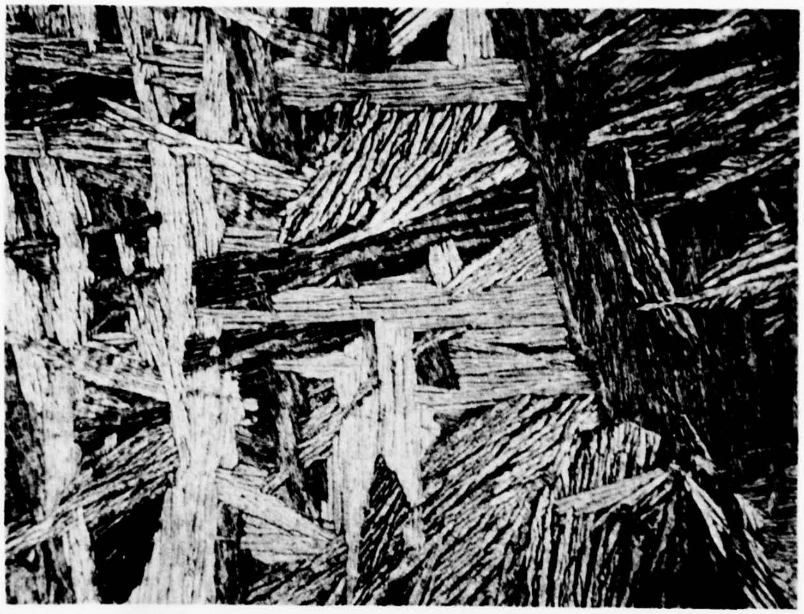


Plate No. 21041

Microstructure consists of platelike alpha
and intergranular beta.
Heat #8009, 302 BHN

Plate No. 21040

Microstructure consists of acicular alpha
outlined by prior beta grain boundaries.
Heat #9877, 302 BHN.

FIGURE 44 - COMPARISON OF MICROSTRUCTURES OF DIFFERENT
HEATS OF ANNEALED Ti-6Al-4V

Mag: 250X

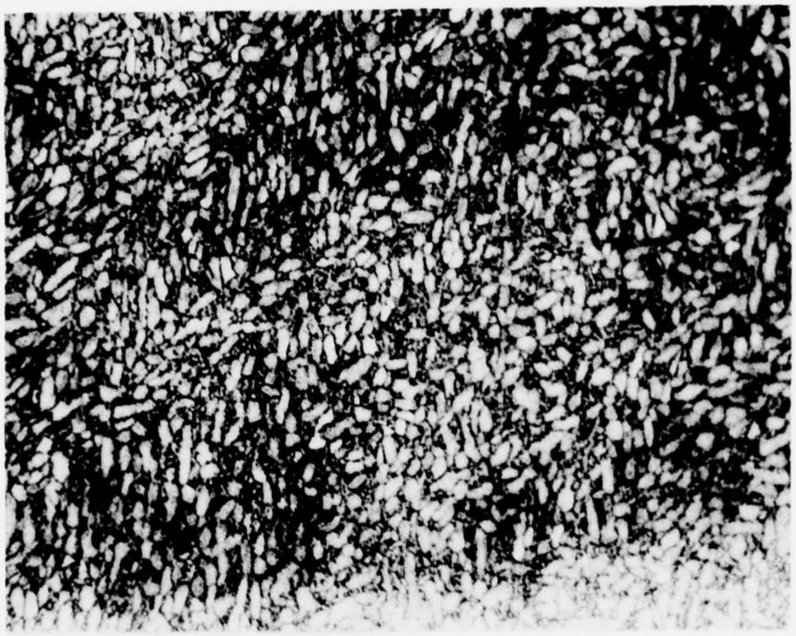


Plate No. 21628

Microstructure consists of primary alpha grains in a matrix of transformed beta.

FIGURE 45 - MICROSTRUCTURE OF McDONNEL DOUGLAS AIRCRAFT COMPANY FORGING - ANNEALED, Ti-6Al-4V, 321 BHN

Mag: 250X

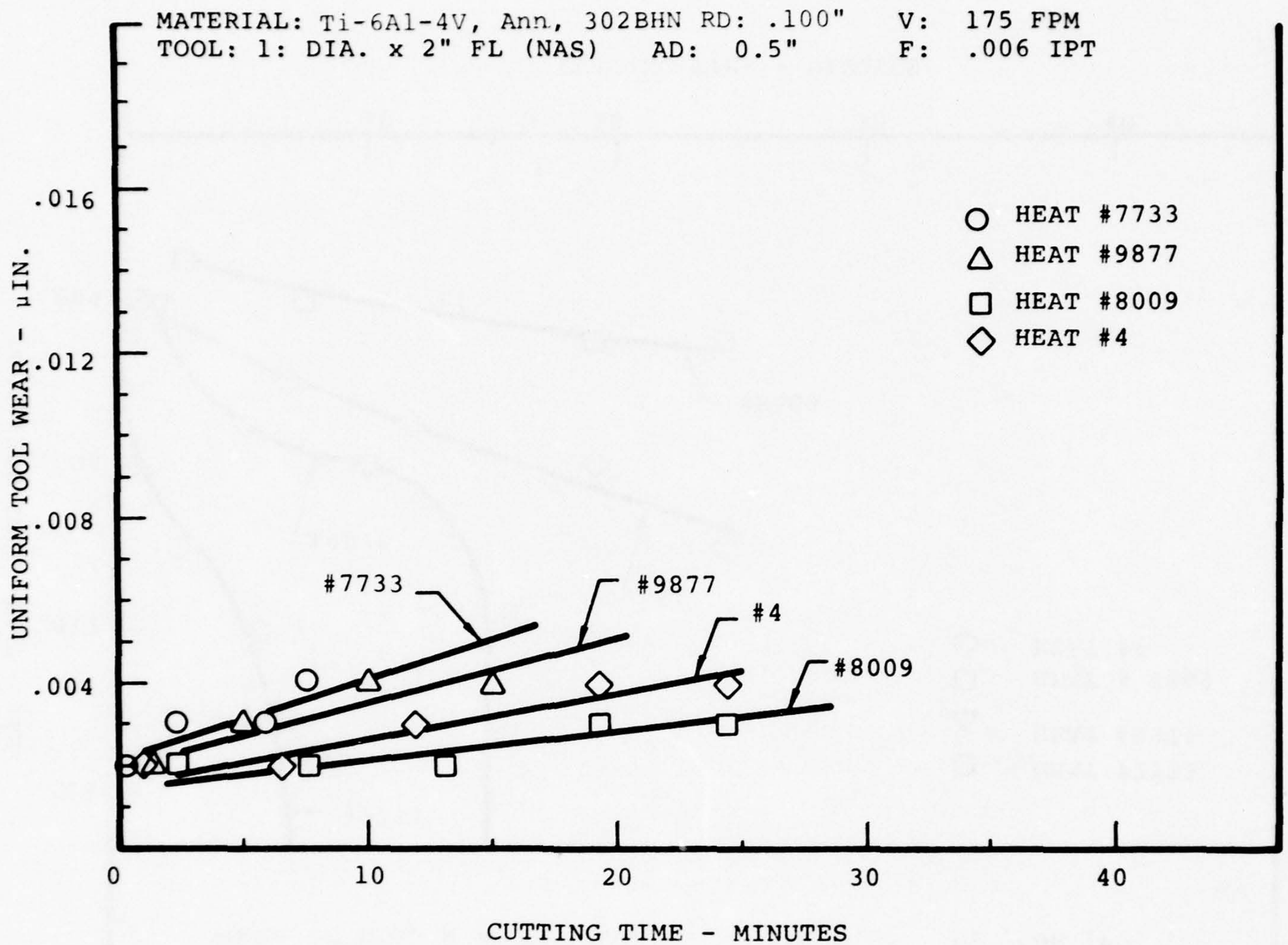


Figure 46 - COMPARISON OF UNIFORM WEAR PRODUCED BY FOUR DIFFERENT HEATS OF Ti-6Al-4V

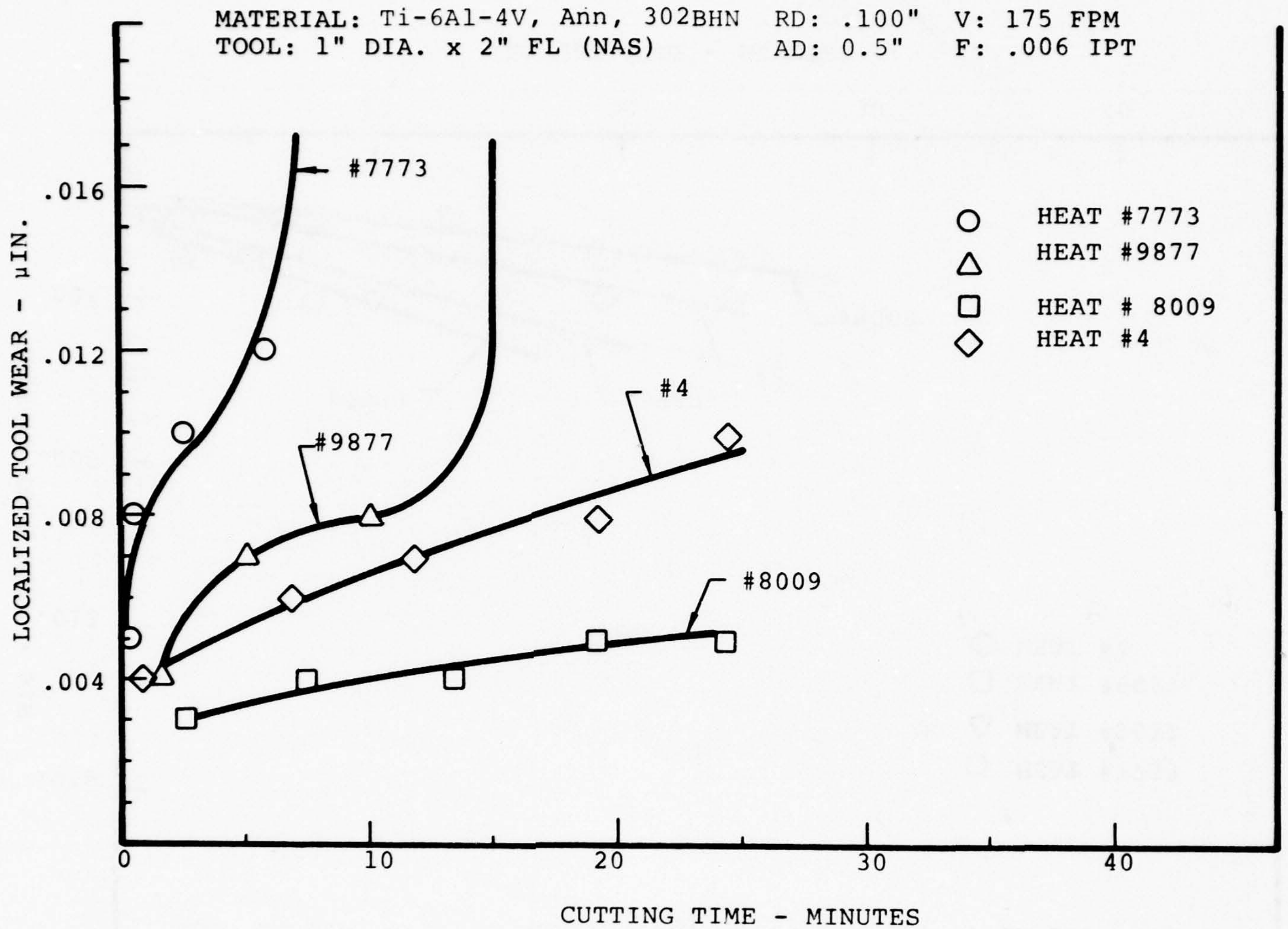


Figure 47 - COMPARISON OF LOCALIZED WEAR PRODUCED BY FOUR DIFFERENT HEATS OF Ti-6Al-4V

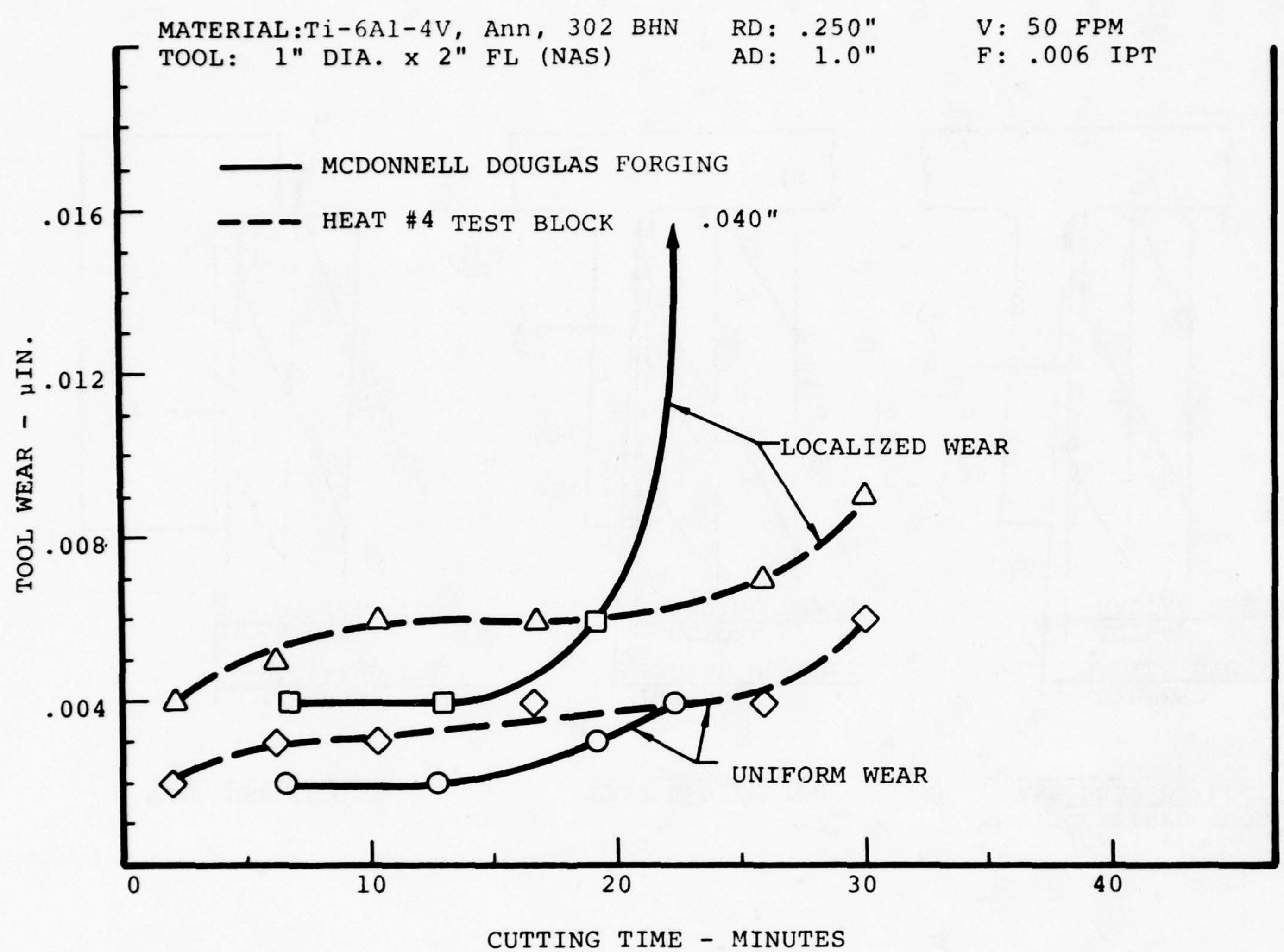


Figure 48 - COMPARISON OF TOOL WEAR PRODUCED BY Ti-6Al-4V TEST BLOCK AND A Ti-6Al-4V AIRCRAFT FORGING

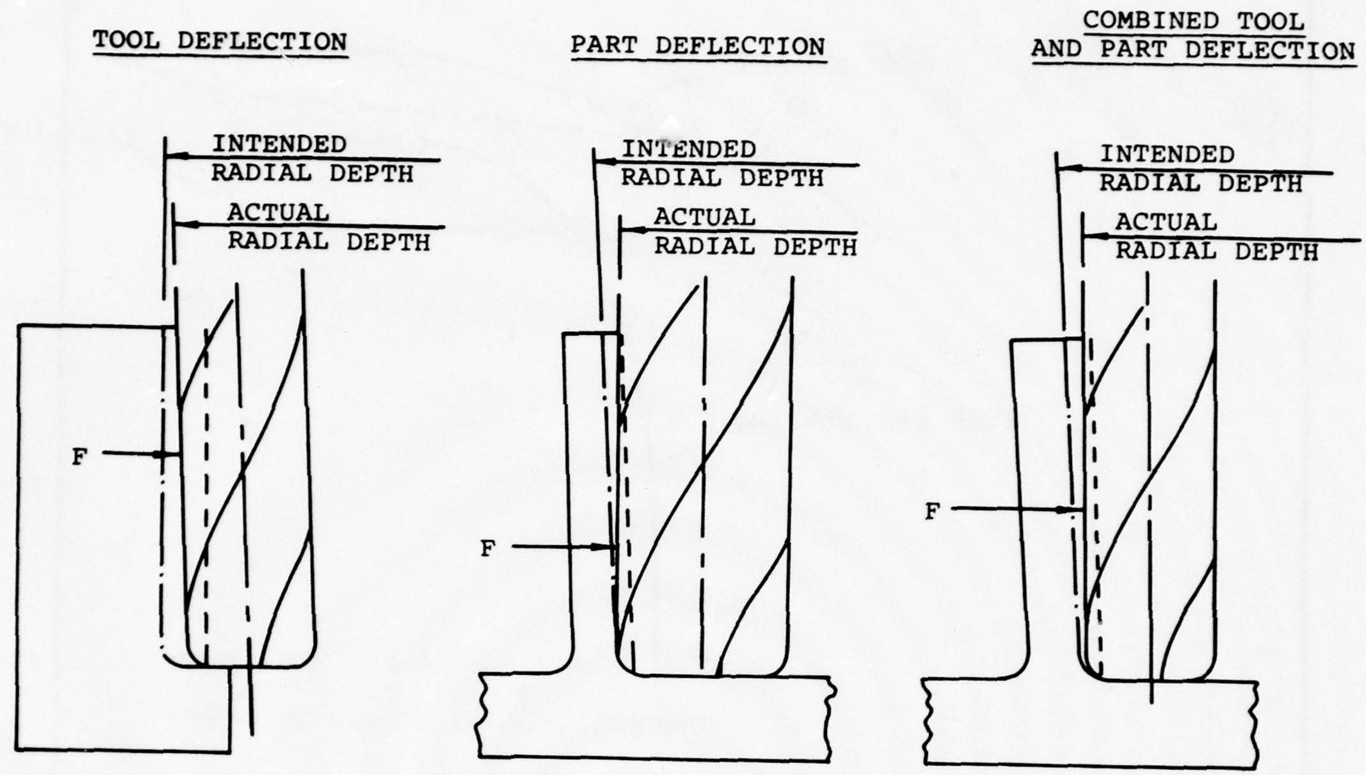


Figure 49 - EFFECT OF TOOL AND PART DEFLECTION ON RADIAL DEPTH

In the first case, the part is rigid, but the tool has a large length to diameter ratio making it less rigid. The tool deflection means that less material is removed at the bottom of the cut than at the top. This causes the resultant force to act at a position somewhat above the center of the axial cut.

In the second case, the tool is rigid but the part is not. This causes the tool to remove more material at the bottom of the cut. The resultant force acts below the center of the cut.

In the third case, both the tool and the part deflect producing a somewhat compensating effect. The location of the resultant force is approximately in the center of the axial depth.

The effect of the shift in the position of the force was negligible for the length of the cutters used in these tests. The impact on the least rigid cutter used would be approximately .5% error in the recorded force.

2.7 Tool Wear Observations During End Milling Ti-6Al-4V Samples

When end milling Ti-6Al-4V, the end mill cutter often failed by chipping of the cutting edges or by a uniform crumbling along the cutting edge when the conditions were especially severe.

Titanium chips curled tighter than steel chips. Consequently, the wear was concentrated on the rake face near the cutting edge. This cratering of the rake face weakened the cutting edge and provided a spot for the metal build-up to begin. As the metal built up, the force on this area of the cutting edge increased until the edge crumbled or chipped. The force on these chipped areas continued to increase until the entire cutting edge crumbled away.

When the conditions were not severe enough to cause visible chipping, the same mechanism of wear was, nevertheless, taking place. In measuring the uniform wear with a Brinell microscope, the reference line was the rake face of the flute. When the reference face was worn away, it had a somewhat self-sharpening effect with the uniform wear on the flank being reduced by the erosion of the rake face.

Metallographic specimens were taken from chipped as well as unchipped areas of the worn end mills to determine if there was any difference in the microstructures of the various tools that would cause some to chip while others did not. No evidence of carbide segregation or of microstructural changes that would account for the chipping phenomena was found. (See Figures 50 and 51). A possible explanation for the differences in performance was the quality of the tool grinding. To overcome this variation, some of the tools were honed lightly by hand before testing. None of the tools that were honed failed by localized chipping. The effect of edge preparation therefore warrants further investigation.

2.8 Cutting Force Formulas for Climb Milling

Formulas for calculating cutting force which were derived by Tlusty and MacNeil (see Appendix D) were modified as discussed below for use in a climb milling application. The modified formulas were derived for the Type II cycle illustrated in Figure 52.

For climb milling, the chip thickness h became,

$$h = S_t \cos \phi \quad \text{(see Figure 53)}$$

The differential of the tangential and radial cutting forces then became:

$$dF_t = KS_t \cos \phi \ dy$$

$$dF_r = 0.3\ KS_t \cos \phi \ dy$$

The resultant force elements dF when applied at the center of the cutter were separated into directions X and Y as shown in Figure 53.

$$dF_x = dF_t \sin \phi - dF_r \cos \phi$$

$$KS_t \cos \phi \ dy \sin \phi - 0.3\ KS_t \cos \phi \ dy \cos \phi$$

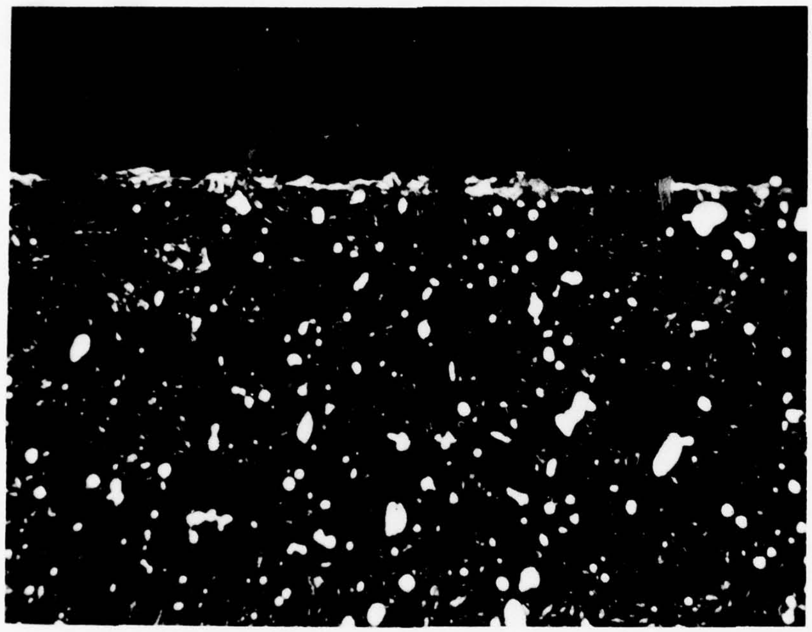
$$KS_t (0.5 \sin 2\phi - 0.3 \cos^2 \phi)\ dy$$

Substituting $dy = r/\tan \beta\, d\phi$ (see Figure 34)

$$dF_x = KS_t (0.5 \sin 2\phi - 0.3 \cos^2 \phi)\ r/\tan \beta\, d\phi$$

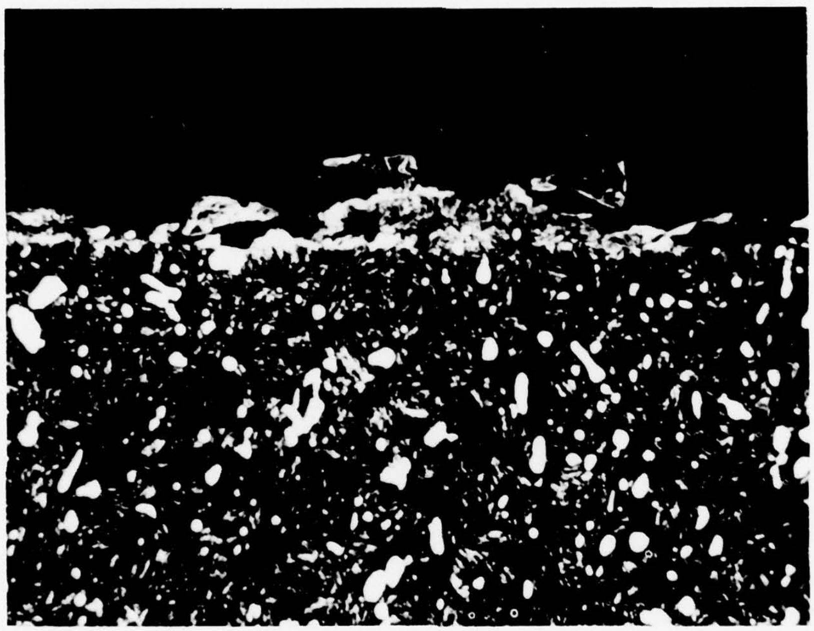
Substituting the unit force $F\mu = 0.5\ KS_t\ r/\tan\beta$

$$F_x = \int - F\mu (\sin 2\phi - 0.6 \cos^2 \phi)\ d\phi$$
$$= - F\mu (0.5 \cos 2\phi + 0.3\ \phi + 0.15 \sin 2\phi)$$



1000X

FIGURE 50 - MICROSTRUCTURE OF UNCHIPPED END MILL



1000X

FIGURE 51 - MICROSTRUCTURE OF CHIPPED END MILL

TYPE II CYCLE FOR LARGE AXIAL DEPTH/RADIAL DEPTH RATIOS

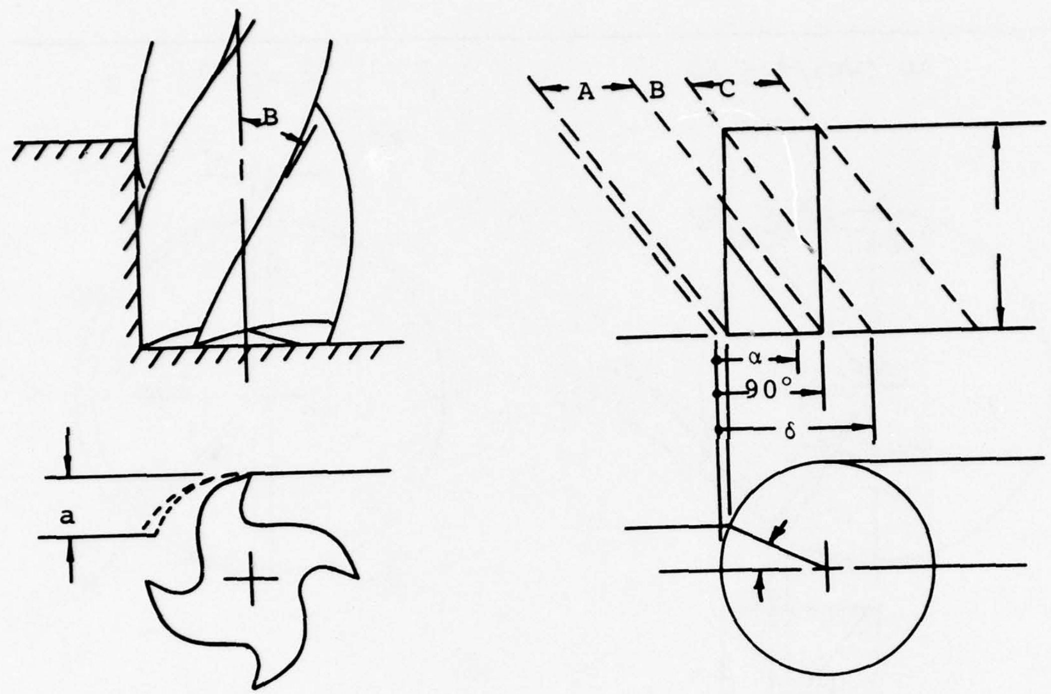


Figure 52 - SKETCH OF UNROLLED SURFACE OF CUT FOR A TYPE II CLIMB MILLING CUT

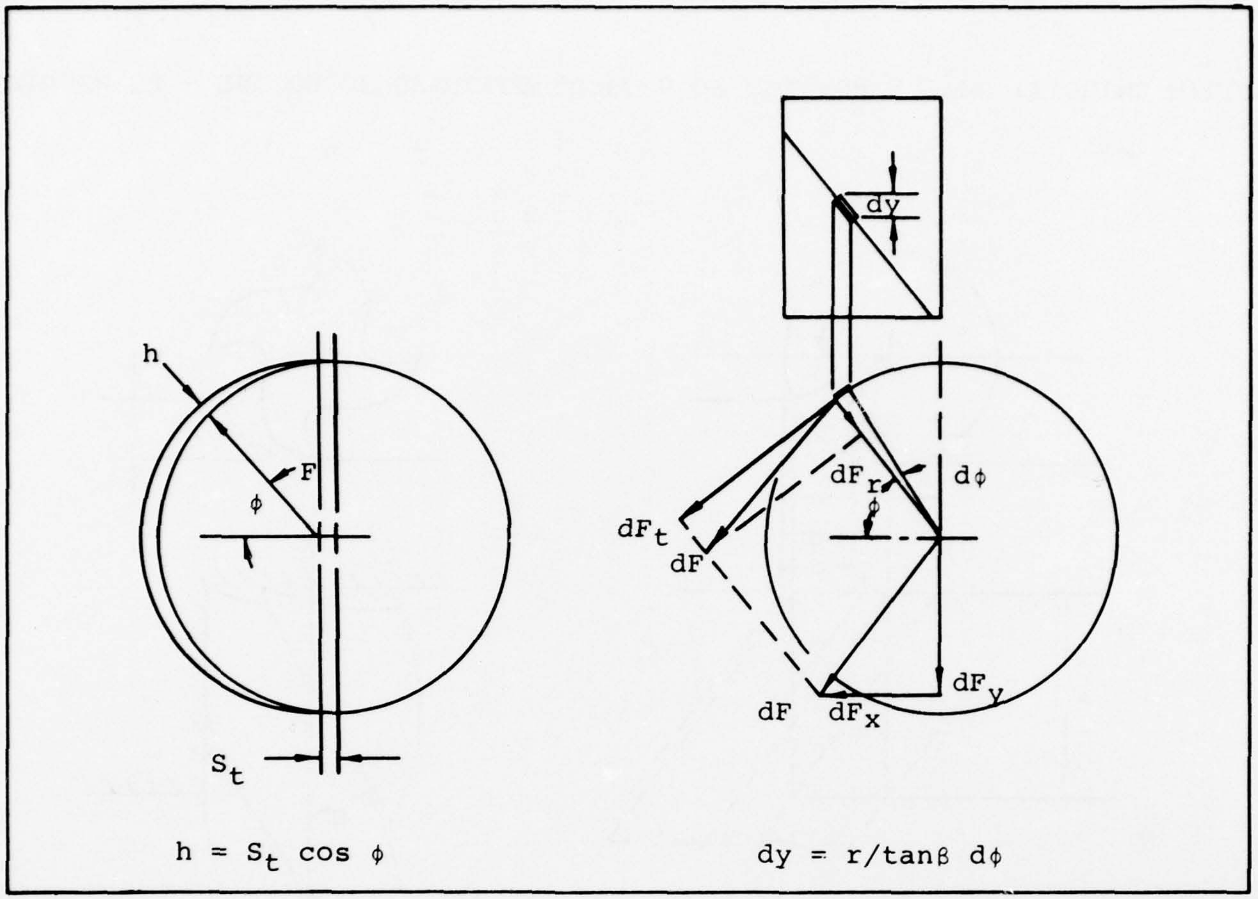


Figure 53 - SKETCH OF CHIP THICKNESS AND FORCE COMPONENTS WHEN CLIMB MILLING

Using the same method, the transverse force, F_y became:

$$dF_y = dF_t \cos \phi + dF_r \sin \phi$$

$$F_y = \int F\mu \,(2 \cos^2 \phi + 0.3 \sin 2\phi)\, d\phi$$

$$= F\mu\,(\phi + 0.5 \sin 2\phi - 0.15 \cos 2\phi)$$

The resultant force was then calculated:

$$F_R = \sqrt{F_x^2 + F_y^2}$$

These expressions were then entered into a computer which plotted F_R within the following limits: Phase A (θ,α); Phase B (θ,π); Phase C $(\alpha-\delta),\pi$)

Figure 54 shows a force plot generated by the computer for one tooth of a 3/4", 4-flute end mill under the following conditions:

Axial Depth: 1.5"	Feed: .0024 ipt
Radial Depth: .119"	Speed: 50 fpm

Figure 55 shows force plots generated by the computer showing the force of the second tooth superimposed on the force of the first tooth. These forces were the instanteous peak forces experienced by the cutter teeth while the forces recorded during the test cuts were the average of these forces during several revolutions.

This difference may in part account for the failure of some cutters when the measured force was well below the theoretical strength of the cutter.

END MILL DIA (IN.)=	.750
HELIX ANGLE (DEG)=	35.00
RADIAL DEPTH (IN.)=	.119
AXIAL DEPTH (IN.)=	1.500
THETA (DEG)=	3.300
DELTA (DEG)=	163.778
MAX FR=	1.199

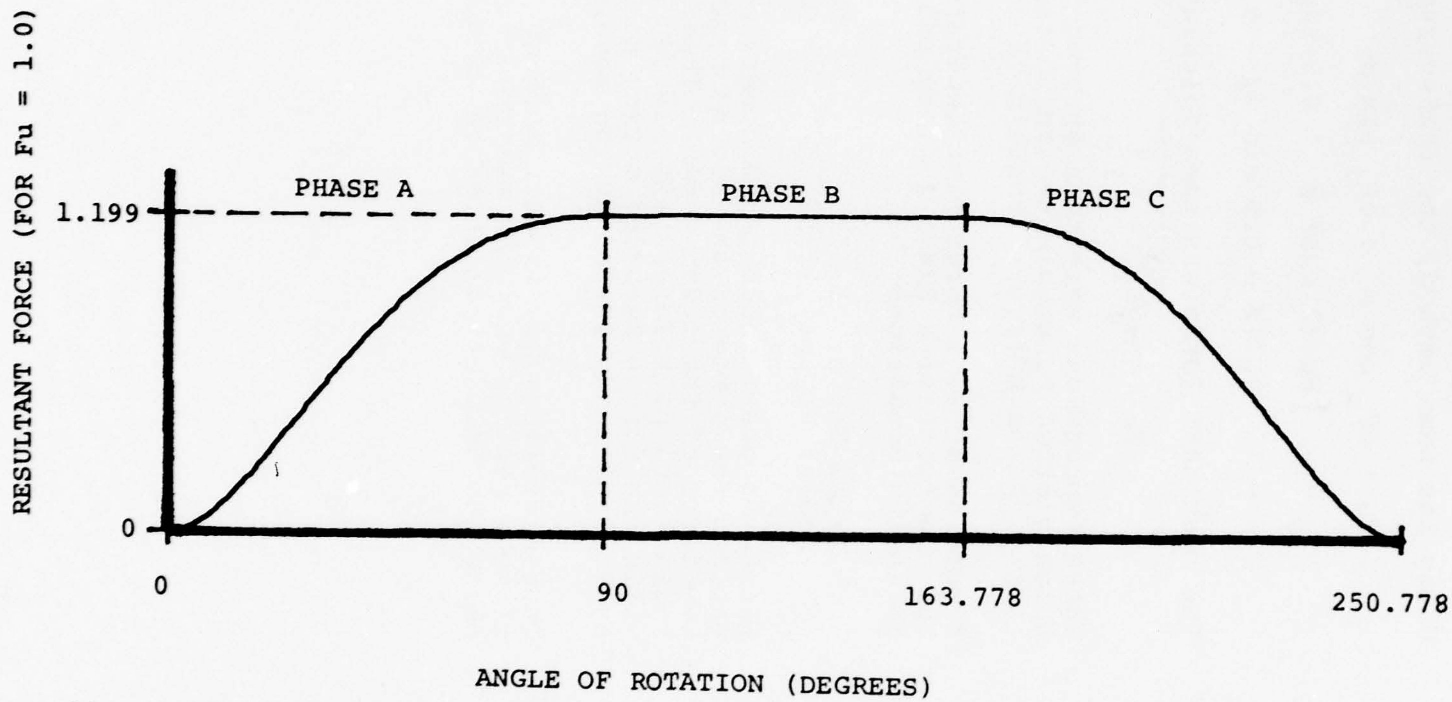


Figure 54 - COMPUTER GENERATED PLOT OF RESULTANT FORCE VS. ANGLE OF ROTATION FOR SINGLE TOOTH END MILL

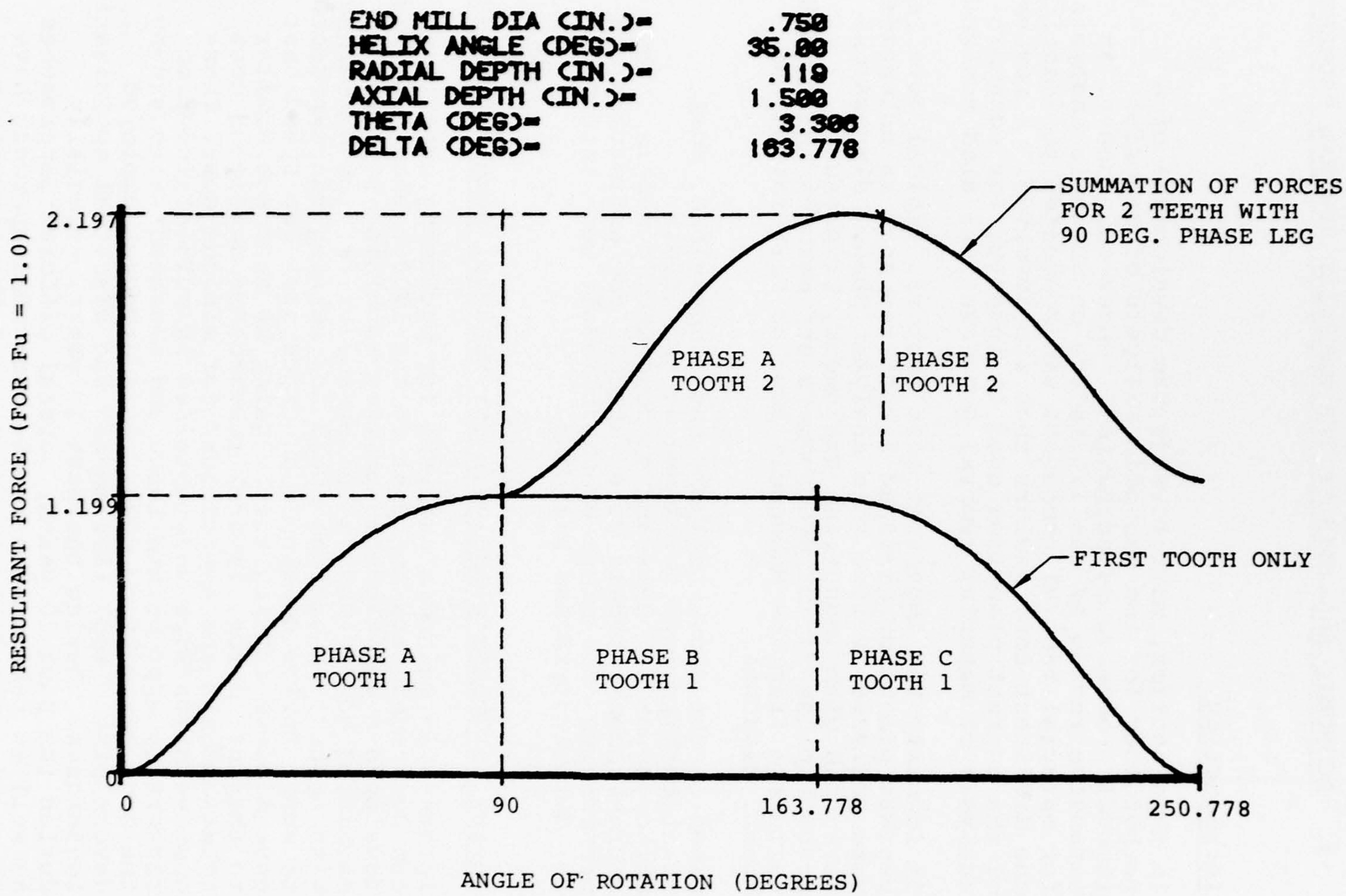


Figure 55 - COMPUTER-GENERATED PLOT OF RESULTANT FORCE VS. ANGLE OF ROTATION FOR A 4-FLUTE END MILL

3. ECONOMIC ANALYSIS OF THE MATERIAL REMOVAL PROCESS

3.1 Introduction

In this section, work towards the development of a methodology for the economic analysis of material removal processes is presented. Under this phase, an extensive review of the literature on economic analysis for material removal processes was conducted to identify the different cost factors that are involved. A review of the current practices used in industry for economic analysis of material removal processes was also conducted.

To identify the important cost factors, typical detailed process plans for airframe structures such as bulkheads were analyzed. During this analysis phase, discussions were held with industrial engineers, preplanners, process planners, NC programmers and methods and process engineers from the McDonnell Douglas Corporation, St. Louis, Missouri.

Based on the above analysis and discussions, cost relationships were developed at two levels: macro-economic models and micro-economic models. The macro-economic models were intended for estimation and preplanning. The micro-economic models were intended for detailed process planning.

3.2 Review of Economic Analysis for Material Removal Processes

Interest in economic analysis for machining operations can be traced back at least to the 1900's when F.W. Taylor developed a relationship between machining time and machining conditions including tool life. By differentiating with respect to cutting speed and setting the expression to zero, Taylor developed an expression for speed that gave minimum cutting time. Using an approach similar to that of Taylor, several researchers developed cost relationships and expressions for minimum cost. These cost relationships were obtained by multiplying time factors by appropriate labor and overhead rates and by the cost per cutting edge. This approach employed deterministic tool life models and classical optimization techniques. During the past 20 years, especially during the past 10 years, several different approaches as well as refinements to the classical approach have occurred. The following summary of the literature reviewed has been written to acquaint the reader with the major milestones, different approaches and applications of economic analysis for material removal processes.

Economic Models and Analyses for Material Removal Processes

(a) Minimum Cost/Maximum Production Rate Models: Following Taylor's approach, cost and production rate relationships and expressions for minimum cost and maximum production rates have been developed for deterministic Taylor tool life and extended Taylor tool life models, and also for a few other deterministic tool life models listed in Appendix A, Table I. In almost all cases, the expressions for minimum cost and maximum production rates were obtained by classical calculus methods of optimizing one variable at a time.

(b) Maximum Profit Models: Based on some assumptions about demand and supply functions, relationships for profit and expressions for maximum profit have been developed. The machining conditions that give maximum profit lie between those that give minimum cost and those that give maximum production rate.

(c) Statistical and Probabilistic Economic Models: Cost, production rate and profit rate relationships and expressions for minimum cost, maximum production rate and maximum profit rate have been developed using some of the statistical and probabilistic tool life models listed in Appendix A, Tables II and III.

(d) Economic Models for Multiple-Station and Multiple-Tool Machining Systems: Minimum cost, maximum production rate and in a few instances, maximum profit rate expressions have been developed for multiple-station and multiple-tool machining systems such as transfer lines, machining centers, automatics, turret lathes, etc. Although deterministic tool life models are primarily used for this task, a few instances were found in which probabilistic tool life models were applied.

(e) Economic Models and Analysis Based On Cutting Rate-Tool Life Functions (RTF): The recently introduced concept of RTF provides a powerful method for determining economic optima considering multiple machining variables simultaneously. The resulting optima are always superior to those obtained by the one variable at a time classical approach.

The above models and methods of analyses are enumerated in Appendix A, Tables I through VII.

Mathematical Optimization of Material Removal Processes:

In addition to the classical optimization methods such as calculus, mathematical programming techniques have been applied to the economic optimization of material removal processes.

(a) Linear Programming Models: Linear programming approaches have been formulated with cost as the objective function and machine tool capabilities such as speed range, feed range and horsepower as constraints. In some instances, tool life was also considered as one of the constraints. Other constraints found in some of the models were: cutting force, torque, deflection, surface finish, chatter, etc.

(b) Geometric or Quadratic Programming Models: When the tool life relationships are nonlinear or second order linear in logarithmic space, the cost and production rate objective functions become quadratic. In such instances, the optimum, rather than lying at one of the apexes of the convex region defined by the constraints, is found within the interior of the convex region. Although some attempts towards formulation of the geometric and quadratic models for material removal processes were found in the literature, few attempts were found towards solution of the problems formulated. It was interesting to note that the concept of RTF may provide a more efficient and direct algorithm to solve the geometric and quadratic programming problems of material removal processes.

(c) Dynamic Programming Models for Material Removal Processes: The well known techniques of dynamic programming have been used to formulate models for process planning of material removal processes. As yet, few of these formulations have resulted in the successful solution of a material removal problem.

The major mathematical optimization approaches are summarized in Appendix A, Table VIII.

Applications of Economic Models and Analyses:

The important applications of economic models and analyses were found to be the following:

(a) Process Planning and Optimization: The selection of a sequence of operations and operating parameters such as tools, speeds, feeds, depth of cut, etc., involved applying economic models to process planning. Since the late 1960's, considerable attention has been drawn to this area. Although some attempts have been made to formulate process planning algorithms based on varient (similarity to already available plans) and generative (computations using mathematical models of the process) approaches, the efforts in this area remain in the embryonic stage.

(b) Adaptive Control: With the advent of adaptive constraints control (ACC) and adaptive optimization control (ACO), the need for algorithms based on the economic model of the material removal process has become pronounced. The practical ACC system now available uses maximization of material removal rate as the indirect index of economic performance. As yet, adaptive control systems (either ACC or ACO) which use real time on line economic algorithms have not reached the production floor.

(c) Computer Aided Economic Anlyses and Optimization: Although many economic models of the material removal processes involve numerous terms and lengthy expressions, they can be readily solved using a calculator provided one takes some time to do the computations. With the advent of the computer these tedious computations could be done quickly, hence several attempts at computerization of the economic models of material removal operations were found in the literature. Now, with programmable calculators and microcomputers, the calculations can even be carried out on the shop floor. Remote terminals and computer graphics are also rapidly advancing the potential of conducting economic analysis of material removal operations especially for NC, CNC, DNC, AC, and CAM systems.

(d) Scheduling Methods: Economic models of material removal operations play a central role in scheduling since the time and cost of routing a part through a given shop facility strongly depends on the reliability and accuracy of the estimates for completion of each of the material removal operations. Job shop scheduling and group scheduling are two approaches that have been applied to this problem. Applications to practical problems are not yet widespread since the basic approaches are still in formative stages.

The following conclusions were drawn from the literature review:

(1) Although the literature was rich in economic models and analysis methods for machining operations, the total cost and production time relationships for the entire material removal manufacturing process have not been fully developed.

(2) Most economic models found in the literature required detailed information about the process which was available only after or during the stages of detailed process planning. Economic models for preplanning and cost estimation of material removal operations are still required.

(3) Although computerized economic analysis was feasible with some of the methods, a systematic use of data base, computer graphics and interactive programs is still needed to encourage widespread use of economic analysis during preplanning and detailed planning.

3.3 Use of Economic Models and Analysis of Material Removal Processes in Aerospace Companies

A review of the current pre-planning and process planning activity in two selected airframe manufacturers and one jet engine manufacturer indicated that the need for a systematic economic analysis of processing alternatives was well recognized by pre-planners, process planners, NC programmers, and methods and process engineers. Although few explicit economic models are in use today, there were scattered yet identifiable efforts towards development of such models in the companies visited.

In practice, however, pre-planners and process planners still relied on their own experience to select the processing sequence and details of the operations. This situation deprived any one individual planner or analyzer of the considerable experience which they collectively represent, and which, when captured in the form of a technology data base, could form the basis of rational and systematic evaluation of economic alternatives during process planning.

As evidenced by the description of stages that follows, the need for the concept of a component/subassembly/assembly evaluation of economic alternatives is present until final production: (1) concept/design stage: which of the manufacturing processes that are capable of producing components to the desired design specification, are low cost and can be executed in the available or potentially available plant facilities? (2) process/material development stage: what are the cost-effective manufacturing processes and materials that can be developed to meet concept and design requirements? (3) cost estimation/value analysis/pre-planning stage: of the available or potentially available processes, which sequence will yield economical manufacture of a given batch or series size of a given component/subassembly/assembly? (4) detailed process planning stage: which sequence of operations and which operating conditions for each operation should be chosen so as to minimize the total cost of manufacturing a given batch or series size of a given component/subassembly/assembly? (5) production scheduling and control stage: how should production of a given variety of components through given production facilities be scheduled so as to produce acceptable parts on time and at a minimum cost?

The primary focus of the economic model development in this project was Stage (4) since it forms the basis for the other stages. Some effort was also devoted to Stages (2) and (3).

3.4 Identification of Cost Factors During Manufacturing Of Aerospace Structures

To identify the various cost factors involved during manufacturing of aerospace structures, detailed process plans of several airframe structures were examined. A few selected detailed process plans were analyzed step by step to identify the major expenditures of time and

money as well as alternative processes that might have been used. The analysis for one airframe structure and a list of the associated cost drivers are presented in Figure 56. The following conclusions were drawn from the analysis:

(1) A major aerospace structure may require as many as two hundred distinct processing steps. The material removal steps represent a significant portion of the total time and cost.

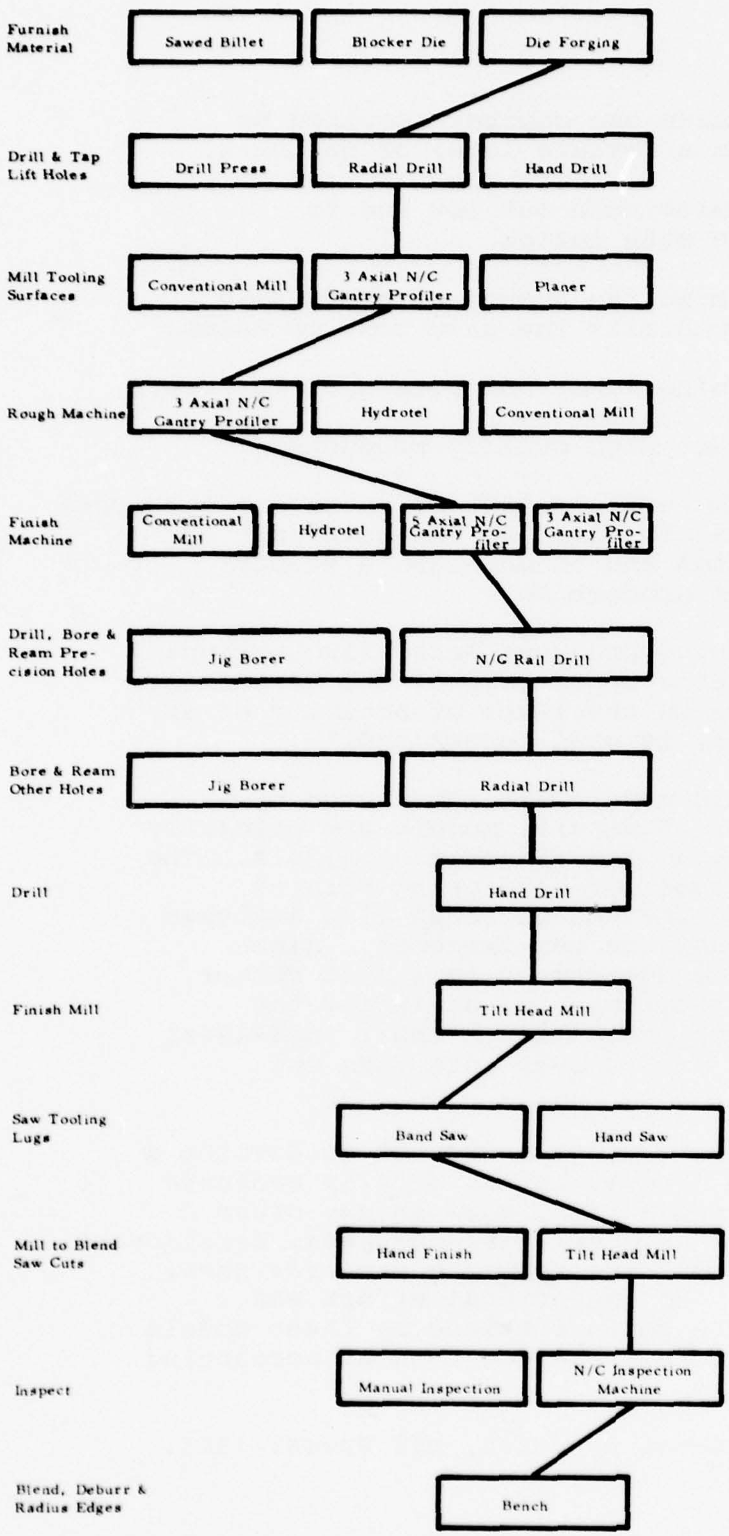
(2) The alternatives during material removal are primarily based on: (a) different machine tools, (b) different cutting tools, tool sequences and cutter paths, and (c) different speeds and feeds.

(3) Since several non-material removal steps are involved, any economic model for airframe structures must be able to evaluate these processing steps as well.

3.5 Development of Economic Models for Material Removal Processes

The scope of the economic model development in this project was limited to the manufacturing process, especially material removal and the other auxilliary operations conducted during discrete parts manufacturing. The economic models were designed to analyze the production time and cost impact of available alternative ways of manufacturing a given batch of discrete parts specifically for aerospace structures. These economic models are useful for (a) process development, (b) cost estimation, value analysis and preplanning, and (c) detailed process planning. The models can be used to obtain the most economical sequence of operations and to optimize the individual operations themselves.

It is necessary to emphasize the scope and the objective of the economic models because within a corporation there exist, implicitly or concretely, several different economic models to satisfy different and often conflicting objective, for example:



Cost Drivers:

Material and Type (forging, billets, etc.)

Overall Dimensions

Flange Height/Thickness Ratio

Web Thickness/Area Ratio

Tolerance (dimensional and weight)

Finish

Number of Pockets and Sizes

Corner Radii

Fillet Radii

Number of Angle Flanges and Degree of Angle to Plane of Part

Parabolic Surfaces

Concave and Convex Surfaces

Flange Heights not Constant

Heat Treatment Requirements

Inspection Requirements

Mold Line Surfaces - Linear Angle Change

FIGURE 56 - PROCESSING ALTERNATIVES FOR ONE AIRFRAME STRUCTURE

Finance:	To minimize the capital required to maintain a certain level of business.
Accounting:	To minimize cash outflow and to maximize cash inflow.
Marketing:	To maximize the amount of goods sold and to minimize the unit cost of sales.
Personnel:	To minimize labor and personnel turnovers.
Engineering:	To produce high quality products.
Production:	To maximize the amount of goods (or services) produced, to minimize the unit cost of production and to maintain a steady level of production.

Industrial dynamics, which produces large fluctuations and time lags in the activity of each of the departments as a result of a change in the level of activity of any one or more departments, is well recognized.*

The most common economic models are those used by finance and accounting. Financial models are primarily used for capital budgeting and financial analysis. The accounting models are used for developing balance sheets, profit and loss statements, cash flow analyses and for federal and other tax requirements. Since these models look at the department as a cost center, they are not generally suitable for analyzing the individual manufacturing processes or their individual work centers which may extend over more than one department.

Indeed, the object of this project was not to develop a better cost accounting system, but *to develop economic models which use production time, cost or any other suitable economic index as a means of analysis, development, planning, optimization and control of a discrete parts manufacturing process.* No intentional effort was therefore made to relate costs obtained by these models with those provided by other systems such as accounting.

* Jay Forrester, *Industrial Dynamics*, MIT Press, 1961.

Concepts:

In the theory of firm, the so-called microeconomic theory*, the production function is defined as the technological relationship which describes the amount of output capable of being produced by each and every set of specified inputs. The production function is defined for a given state of technological knowledge. An important property of the production function is that there are numerous alternative combinations of inputs that produce the same output. However, for any one combination there is only one unique amount of output. Using the above two properties, the condition for the least cost optimum input combinations for any given level of outputs can be derived. For two inputs, say labor and machines, the least cost optimum combination occurs at a point where the isocost (equal cost) line is tangent to the isoquant (equal amount of output) line.

This well known property is exhibited by the discrete parts manufacturing process as well as by the individual operations within the process. Hence, for a given batch and/or series size (at an acceptable level of quality), there exists a sequence of operations and a combination of operating conditions within each operation for which the total manufacturing cost is a minimum. Similarly, optima for production rate, profit rate and other related economic parameters exist, although they may occur at different input combinations. This is the basic premise and motivation for the development of economic models for discrete parts manufacturing processes.

Economic Models:

The economic models developed in this project were based on the following observations:

(1) A typical discrete parts manufacturing process such as that used in aseospace companies consists of several individual work centers (e.g., machine tools, heat treating facilities, forging presses, inspection stations, etc.) which are scattered over one or more production departments within a plant or within several plants of a company or several companies. Figure 57 shows a schematic diagram of a manufacturing process.

* Paul A. Samuelson, *Economics*, Tenth Edition, McGraw-Hill Inc., 1976.

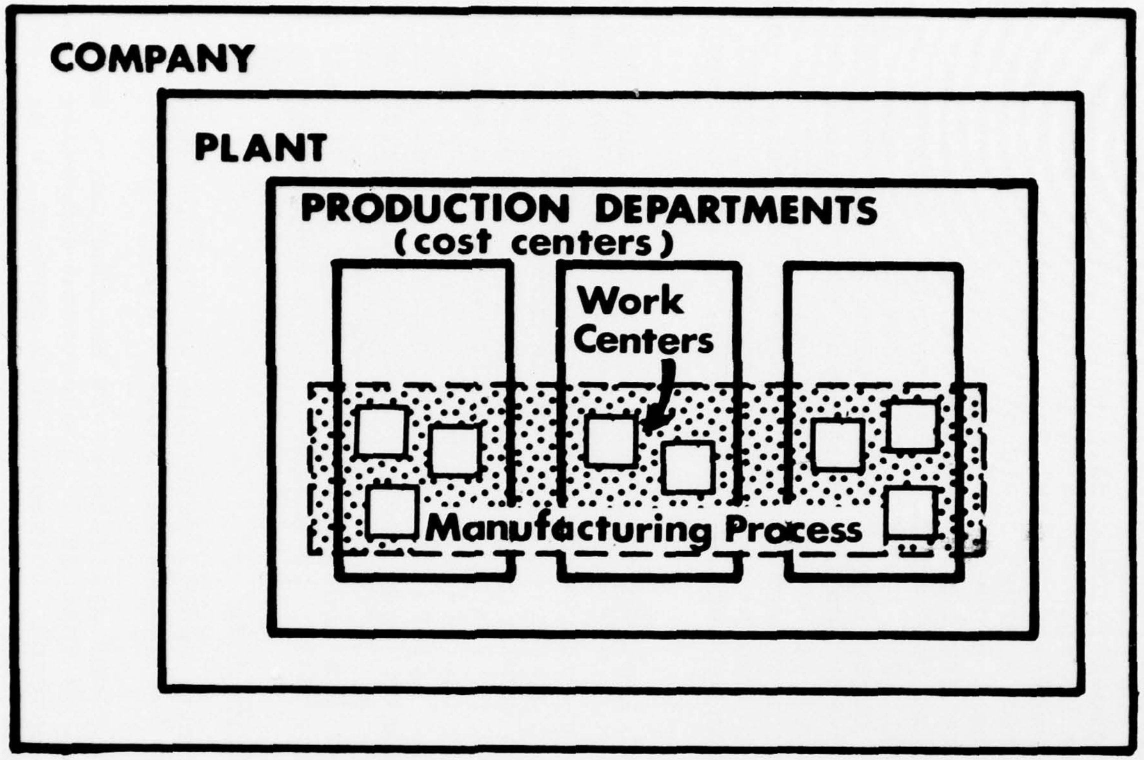


Figure 57 - MANUFACTURING PROCESS FOR DISCRETE PARTS TYPICALLY INVOLVES WORK CENTERS IN SEVERAL PRODUCTION DEPARTMENTS WITHIN A PLANT OF A MANUFACTURING COMPANY

(2) The productive time within which a work center performs its processing is composed of: (a) setup, load/unload time, (b) processing time and (c) time lost in process interruptions for adjustments, tool changes, etc. Figure 58 illustrates the relationship between lead time, productive time and floor-to-floor time. The floor to floor time is productive time + slack time allowed, and the lead time is productive time + non-productive time. The slack time and non-productive time are recognized to be characteristic of a given personnel and equipment utilization efficiency*. The economic models under development in this project were concerned with the productive time only. Appropriate equipment and personnel utilization factors must be added to the productive time if estimates of floor to floor or lead times are required.

(3) The cost elements associated with the productive times of each of the work centers of a manufacturing process are obtained by multiplying each of the components of the productive times by appropriate labor and overhead burden rate and by adding the appropriate direct and indirect material and auxilliary costs associated with that work center. A typical set of variable cost factors associated with a work center are shown in Figure 59.

The generalized equations for total productive time and the associated total cost for a manufacturing process are as follows:

Total Productive Time =

$$\sum_{j=1}^{k} \left[(m_o)_i + \left(\frac{m_1}{R}\right)_i + \left(\frac{m_2}{RT}\right)_i \right]_j \tag{35}$$

and Associated Total Cost =

$$\sum_{j=1}^{k} \left[(k_o)_i + \left(\frac{k_1}{R}\right)_i + \left(\frac{k_2}{RT}\right)_i + (\text{material cost})_i \right]_j \tag{36}$$

*B. Colding, "The Total Cost Relationship of the Integrated Manufacturing Systems", Manufacturing Systems (CIRP), Vol. 13, No. 2, 1974, p. 109-132.

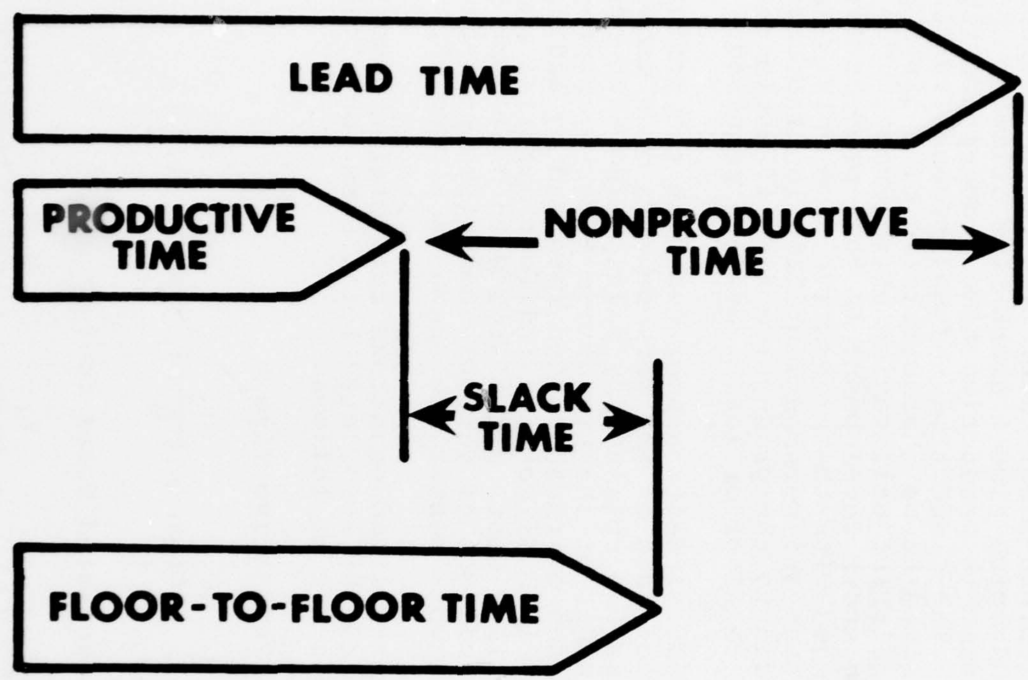


Figure 58 - RELATIONSHIP BETWEEN LEAD TIME, PRODUCTIVE TIME AND FLOOR-TO-FLOOR TIME (AFTER COLDING, 1974)

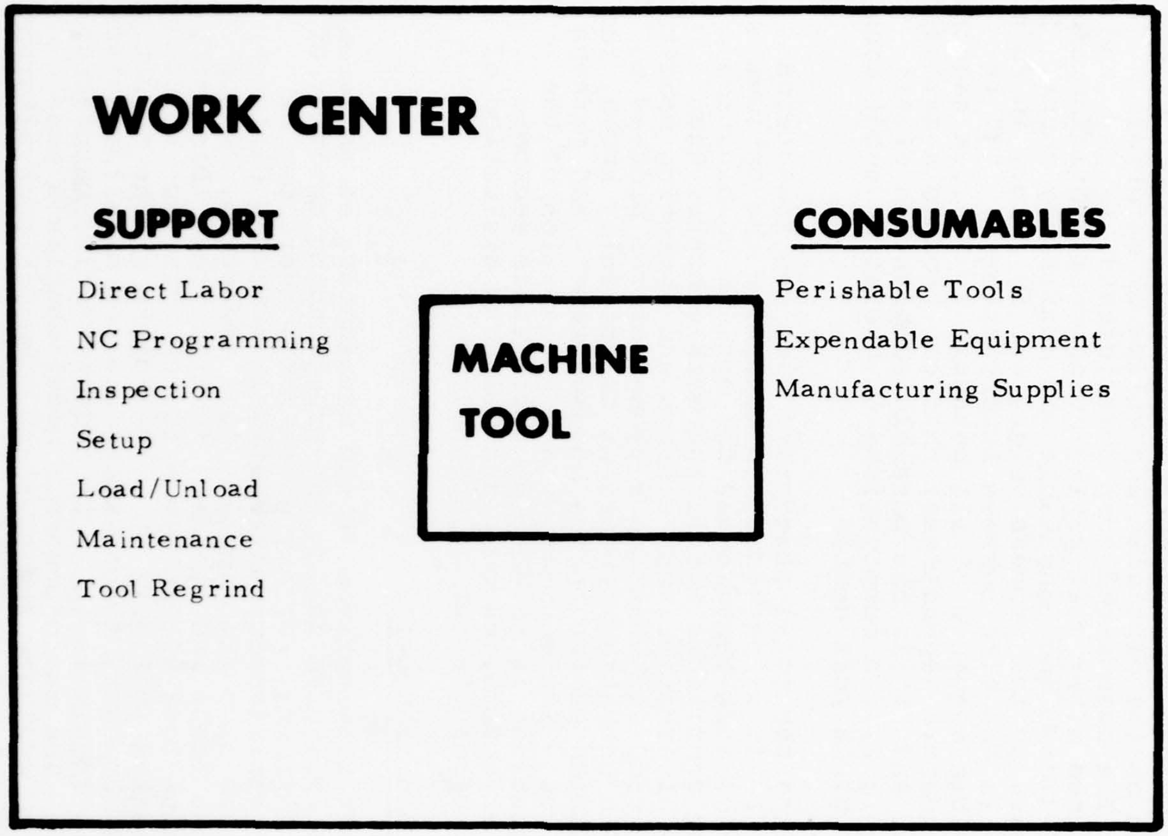


Figure 59 - WORK CENTER IS DEFINED AS AN IDENTIFIABLE PROCESSING UNIT THROUGH WHICH DISCRETE PARTS ARE PROCESSED

where m_0, m_1, m_2 are time coefficients related to setup and load/unload processing and interruptions. They are dependent on the part size and volume of material removed. The associated cost coefficients, k_0, k_1, and k_2 are obtained after multiplying by appropriate labor and overhead rates, and consumable and auxilliary costs. R is the rate of the process, e.g., cu. in./min., in./min., etc.; T is the time between interruptions.; "j" is one possible sequence of all possible 1, 2, ...k sequences of work centers (operations) that can produce a satisfactory component and "i" is one possible combination of all possible 1, 2,...n combinations of operating conditions within a given work center.

To minimize the total productive time and associated total cost, it is necessary to determine the optimum sequence of work centers and the optimum combination of operating conditions within the work centers. When numerous alternative work centers and operating conditions are involved, and when the response of the process to changes in operating conditions is not fully known, the determination of the optima becomes remote and perhaps meaningless. The most important application of the above equations is to develop appropriate economic models for a detailed cost analysis and evaluation of alternative manufacturing processes.

3.5.1 Macro-Economic Model

Processing alternatives in the manufacture of an aerospace part are evaluated during the pre-planning activity of process planning. For any given part, there may be numerous satisfactory alternatives including different machine tools, cutting tools, tool sequences, cutter paths, and feeds and speeds. To illustrate this fact, the machine tool alternatives for one airframe structure are presented in Figure 56. Regardless of the operation selected, however, there exists one set of alternatives that will result in the most cost effective manufacturing sequence. The macro-economic model enables a pre-planner to evaluate the cost and time for each alternative and to select the most cost effective manufacturing processes.

The generalized time and cost equations (35) and (36) are reorganized for obtaining the following macro-economic model form:

$$t = m_0 + m_1/H_t \quad (37)$$
$$c = k_0 + k_2/H_c + \text{material cost} \quad (38)$$
$$\text{or } c \simeq Mt + \text{material cost} \quad (39)$$

where t and c are time and cost per part for one operation (1,2,...j operations), R = rate of the process, T = time expended to interrupt process for tool change, tool adjustments, etc. H_t, H_c are productivity functions:

$$H_t = R/(1 + m_2/m_1T) \text{ and } H_c = R/(1 + k_2/k_1T)$$

Equations (37), (38) and (39) are applicable to any manufacturing process.

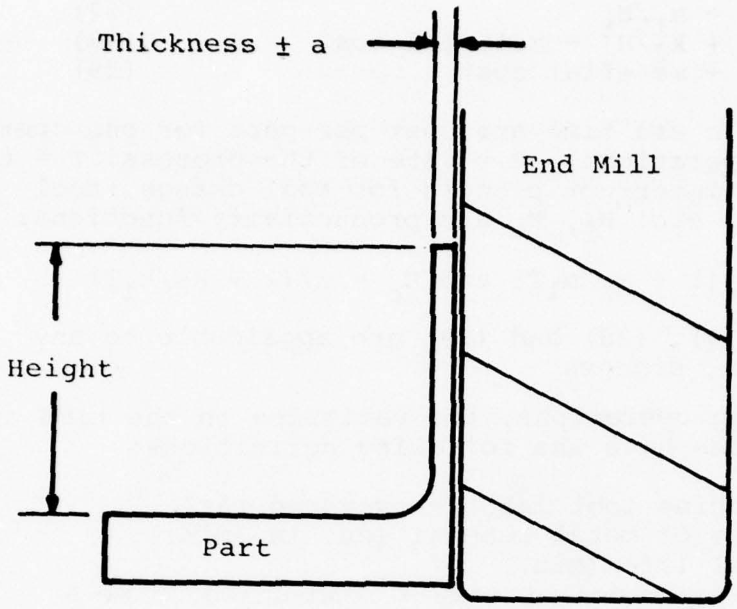
For machining operations, the variables in the time and cost equations have the following definitions:

M = machine tool labor + overhead rate
R = rate of metal removal (cu. in./min.)
T = tool life (min.)
m_0 = setup time/lot size + load-unload time + rapid traverse time
m_1 = volume of metal removed
m_2 = volume of metal removed * dull tool replacement time
$k_0 = m_0 \times M$
$k_1 = m_1 \times M$
$k_2 = m_2 \times M$ + tooling cost

The metal removal rate (R) for the cost and time euqations is characteristic for a certain operation on a particular machine tool with a particular cutter and workpiece material. At this metal removal rate, the tool will last for T minutes. Values for R, T, H_t and H_c are collected for all operations and all alternatives for a particular part family based on the most uncomplicated part geometry. This data comprises the Base Machinability Data.

H_t and H_c must be adjusted for a particular part geometry to reflect the complexity of the part. This is accomplished through the use of cost drivers and cost driver functions. Cost drivers are characteristic of a part which slows down the productivity of the process. Cost drivers include complexities such as surface finish, tolerance, part rigidity, material variations, etc. The cost driver function is the mathematical relationship which describes the reduction in H_t and H_c given cost driver.

An example of a cost driver function where part rigidity and tolerance are the cost drivers (data taken from the example on micro-economic analysis of F-15 former-upper panel, Figure 72), is shown in Figure 60.



$$R = 12FVn(AD)(RD)/\pi d$$
$$= .75 \text{ cu.in./min.}$$
$$H_t = R/(1 + (m_2/m_1)T)$$
$$= 0.68 \text{ cu.in./min.}$$

Actual Cut Data From Operation Sheet (see Figure 72)

End Mill Dia. (d) = 3/4"
Flute Length = 2.00"
No. of Flutes (n) = 4"
Radial Depth (RD) = .100"
Axial Depth (AD) = 1.00"
Feed (F) = 0.007 IPT
Speed (V) = 52.4 FPM
$t_d = m_2/m_1$ = 3 min.

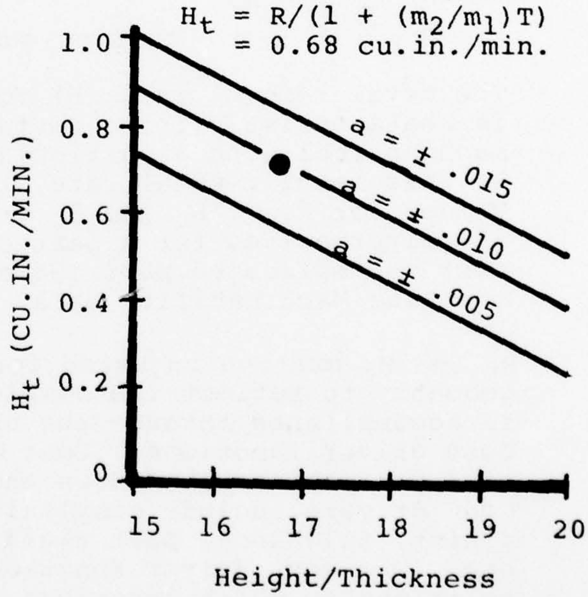


Figure 60 - EXAMPLES OF MACRO-ECONOMIC ANALYSIS ON "FINISH MILL PERIPHERY" OPERATION FOR F-15 FORMER-UPPER PANEL

The cost driver functions (H_t, H_c = f (cost drivers) such as shown in Figure 60 can be developed either through micro-economic analysis or on the basis of subjective judgement of the preplanner. This requires either planned or actual cost data on the part family to which the part belongs. Since such data was not available or obtainable within the scope of the contract, the application of macro-economic model was not pursued.

The macro-economic model is shown schematically in Figure 61. Basic geometry of the part, part code, cost drivers and process alternative are input to the model. Information on base machinability data, cost driver functions, machine tool and cutting tool characteristics and material specifications is obtained from data base files. From this data, values of R and T are selected. Then H_t and H_c are adjusted according to the cost driver function. The cost and time for this alternative is then computed using the time and cost equations (37),(38) and(39). If a new alternative is to be evaluated, the new conditions would be input and the economic analysis repeated. Finally, the alternatives which yield minimum cost or time would be selected as the actual manufacturing process sequence.

3.5.2 Micro-Economic Model

The micro-economic model is useful in detailed planning to aid the planner in the selection of specific operating conditions for a particular operation. For example, for a finish milling operation, the micro-economic model would aid the planner in the selection of cutting tool, cutting fluid, feed, speed and tool change frequency. The model uses the criterion of either minimum cost or maximum production rate to choose these conditions.

In addition to selecting the operating conditions, the micro-economic model provides a complete economic analysis of the operation. This includes costs associated with setup, load-unload, rapid traverse movements, extra travel, metal removal, process interruptions for tool replacement, and tool reconditioning.

As this figure indicates, a simple schematic of the micro-economic model is shown in Figure 62. Economic evaluation at the micro level assumes that detailed information is available about all operations to be considered. For example, detailed cutter paths, tool life information and part configuration must be known for a metal removal operation. In addition, detailed data must be available for all machine tools, cutting tools, material specifications and cutting fluids.

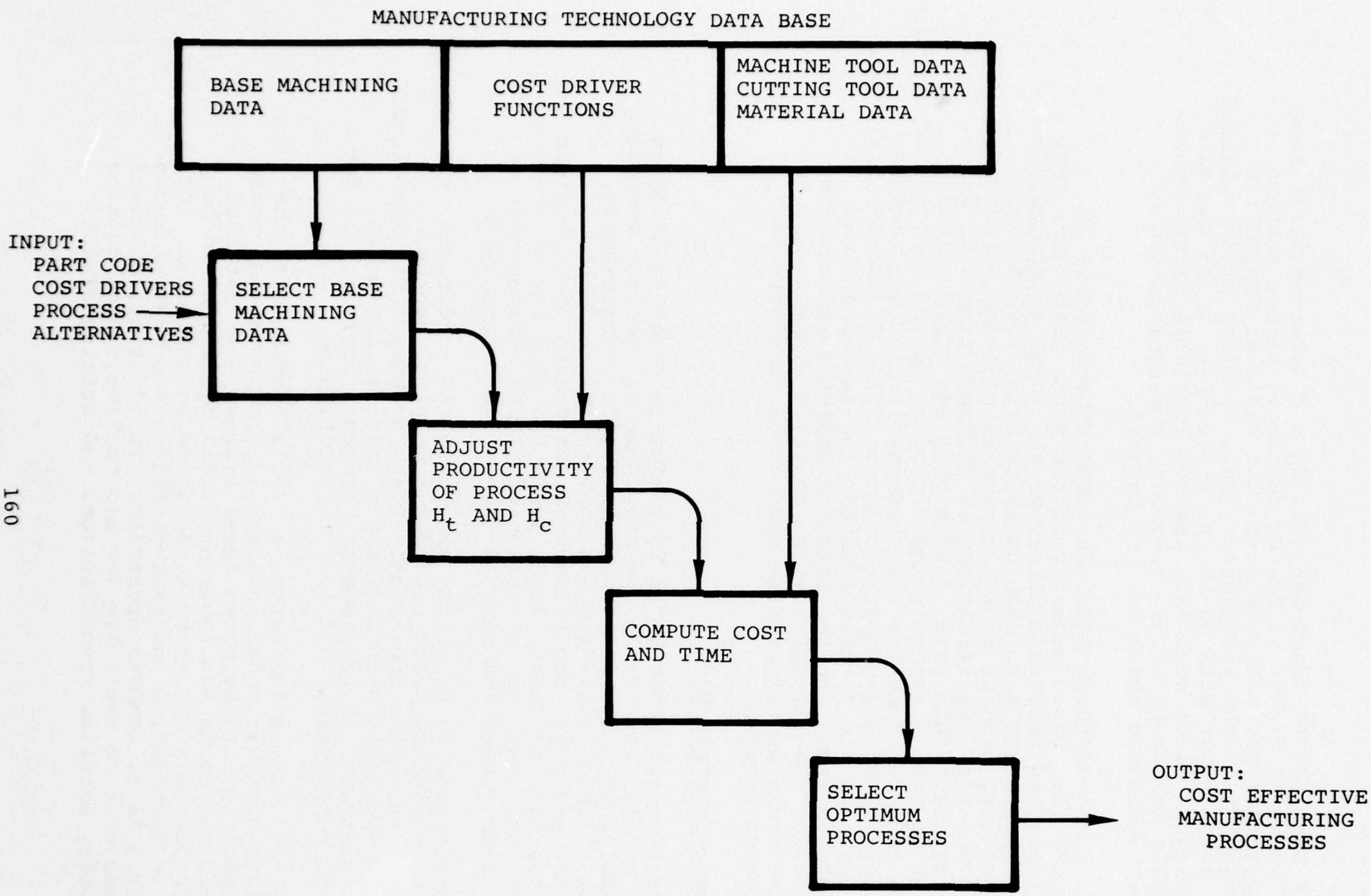


Figure 61 - MACRO-ECONOMIC MODEL DIAGRAM

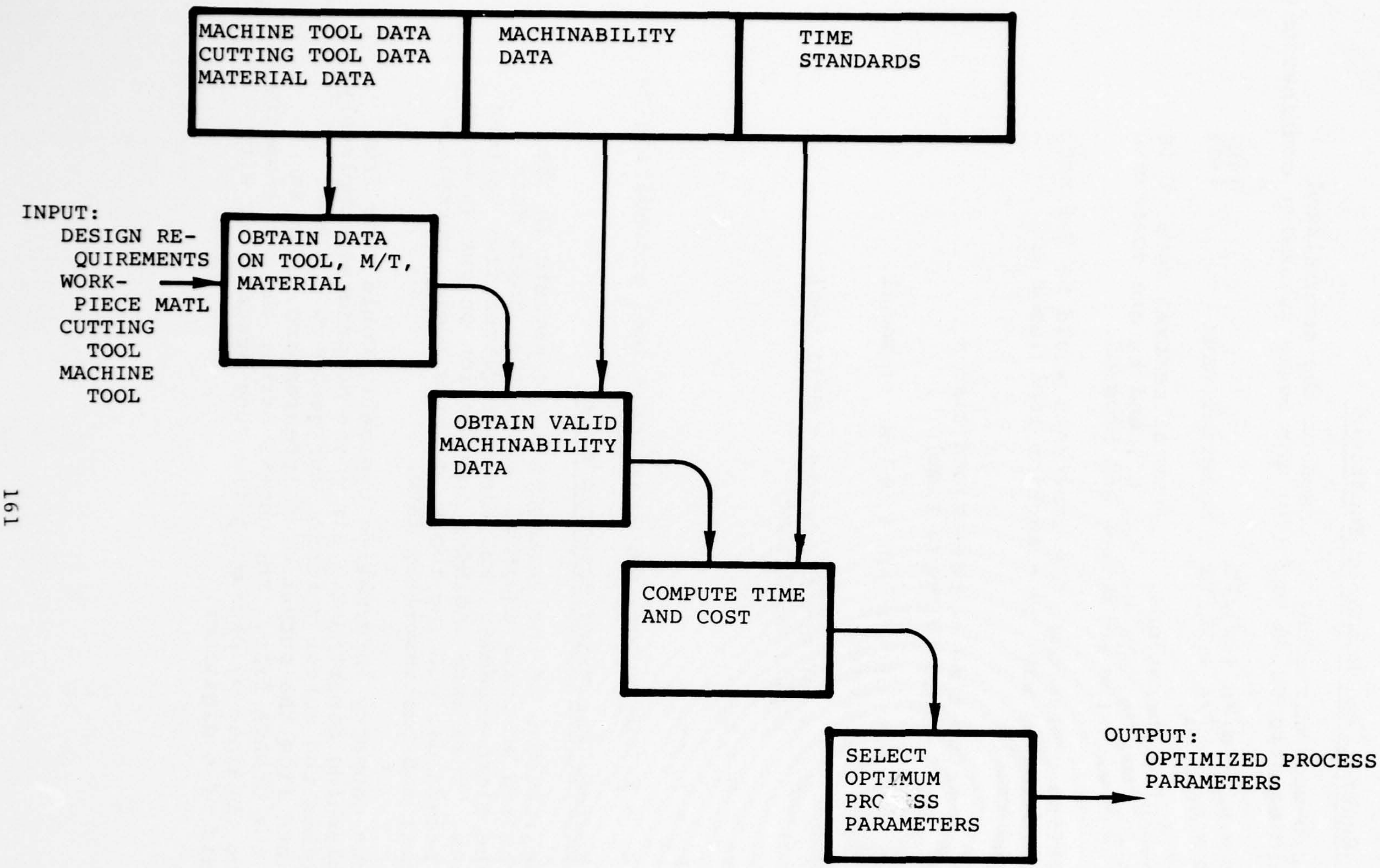


Figure 62 - MICRO-ECONOMIC MODEL DIAGRAM

Use of Generalized Economic Equations

The micro-economic model is based on the generalized economic equations (35) and (40) for every parameter combination:

$$t = m_0 + m_1/R + m_2/RT \qquad (40)$$
$$C = k_0 + k_1/R + k_2/RT + \text{material cost} \qquad (41)$$

For machining operations, R is metal removal rate, T is tool life, and m_0, m_1, m_2, k_0, k_1, and k_2 are constants associated with the workpiece and process.

For milling operations, the constants would be defined in the following way (M = machine tool labor and overhead rate).

m_0 = setup time + load-unload time + rapid traverse time)

m_1 = volume of air cut + volume of metal removed)

m_2 = volume of metal removed * dull tool replacement time

$k_0 = M \times m_1$

$k_1 = M \times m_1$

$k_2 = M \times m_2$ + tool depreciation + tool reconditioning

Data Sources for Micro-Economic Model

The definitions of the variables and constants in the generalized economic equation reveal that input data for the micro-economic analysis is required from various sources. This data includes information on cut geometry, time standards, cutting tools, machine tools, workpiece material and machinability data.

The cut geometry information typically would come from the planning department. Since the NC program completely describes the cutter motions, cut geometry can be obtained from the output of NC programming, such as from the CLDATA file. For non-NC parts, the cut geometry can be obtained by measuring the cuts manually or with the aid of a digitizer.

Time standards are obtained from either manual or computerized systems used by the time standards personnel. Setup and load-unload time standards, dull tool replacement time standards, and cutter reconditioning time standards are required.

Information describing machine tools and cutting tools is normally obtained from the tool manufacturers. This information can be coded into data files for use in the micro-economic model.

Workpiece material specifications must be obtained from manufacturers and include hardness, condition (cast, forged, etc.) and heat treatment. This data is coded into a material data file.

Machinability data can be classified on three "levels" depending upon the source of the data. These levels are used by the micro-economic models in different ways.

The most basic level of machinability data is obtained from machining handbooks. This is classified as "Level 1" data. Typically, a handbook specifies a conservative feed and speed to be used for a certain range of operating conditions. Tool life is normally within a certain range for this data, but the exact tool life is not known. The micro-economic model associates with a Level 1 data point three values for tool life; one value is chosen as the minimum of the tool life range, one as the middle of the range and one as the maximum. This results in a "sensitivity analysis" capability using Level 1 data. The micro-economic model indicates how sensitive the final economics of the part are to tool life.

Level 2 data consists of actual discrete values of feed, speed and tool life which were obtained at a specific depth of cut. This data could be obtained from the production floor or from tool life experiments. The micro-economic model calculates costs for an operation at each discrete point, then chooses the feed and speed which results in minimum part cost as well as the feed and speed which results in maximum production rate.

If a sufficient number of data points are available as Level 2 data, a mathematical relationship relating tool life to feed, speed, and depth of cut can be generated. Level 3 data consists of such mathematical relationships for a certain range of feed, speed, and depth of cut. Level 3 data is used by the micro-economic model to find the feed and speed which results in minimum cost and maximum production rate within the qualified ranges of feed, speed and depth of cut.

Interface Between Macro and Micro Models

As shown in Figures 61 and 62, many of the data types needed for the macro and micro-economic models are the same. The main differences between the two models are the machinability data and the input data. The macro model requires cost driver type input, whereas the micro models require detailed cut geometry.

Since much of the information required for cutting tools, machine tools, and materials is identical for the micro and macro models, a shared data base may be utilized. This interface is illustrated in Figure 63.

The relationship between the mathematical models, micro and macro economic models, cost drivers and part family are given schematically in Figure 64. The mathematical model represents the most detailed level and the part classification code, the coarsest level.

3.6 Application of the Micro-Economic Model to an Aerospace Part

A typical aerospace part was selected on which to demonstrate the capabilities of the micro economic model. The part chosen is called "Former-Upper Panel" and is shown in Figure 65. This part is currently in production at the McDonnell Douglas Aircraft Company in St. Louis, Missouri and is part of the F-15 aircraft. The workpiece material is Ti-6Al-4V and is supplied as a forging.

McDonnell Douglas provided Metcut Research with details of the part such as operation sequence, detailed operation sheets, cutting tool information and machine tool data. Much of this information was coded into data

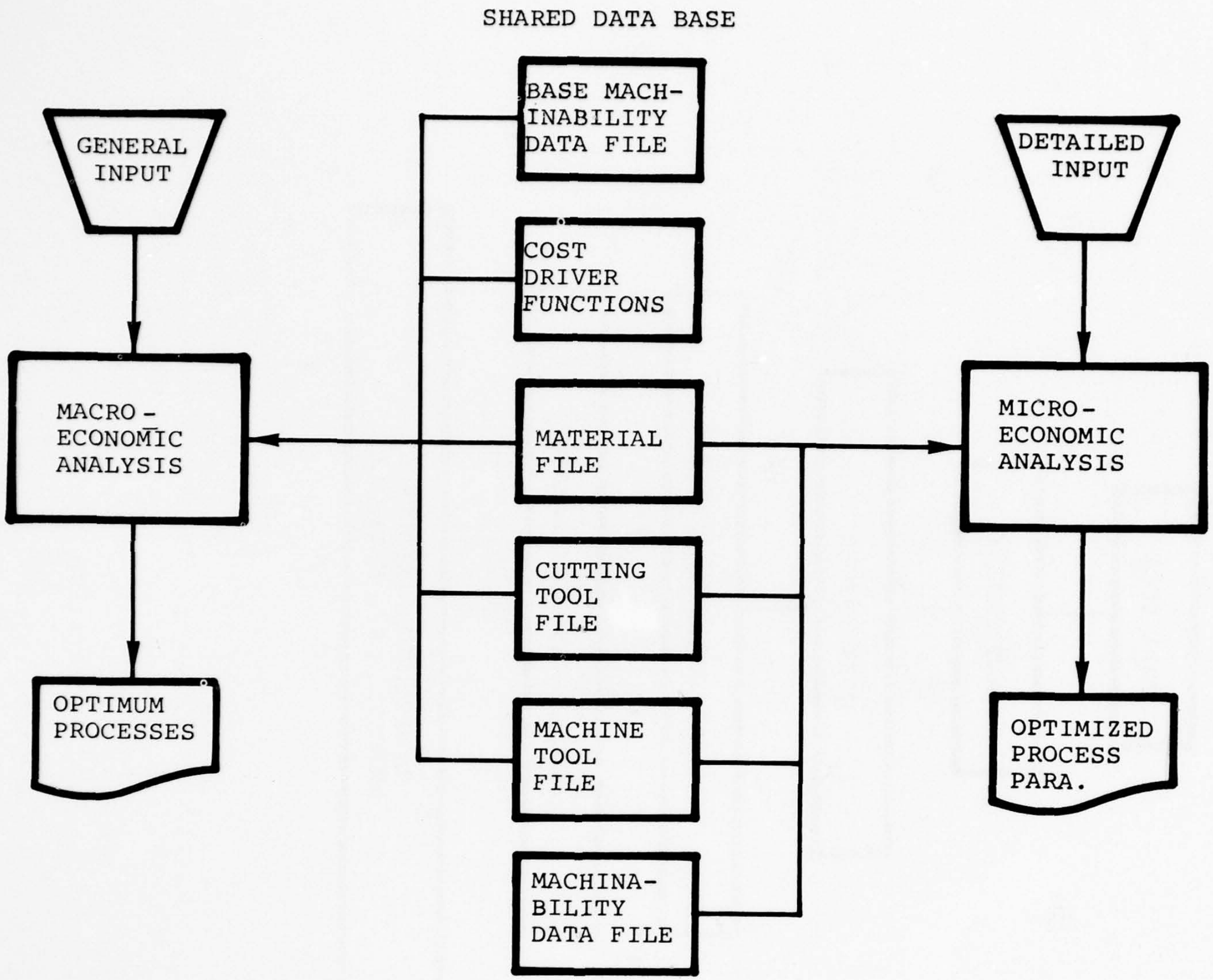


Figure 63 - INTERFACE BETWEEN MACRO- AND MICRO-ECONOMIC MODELS

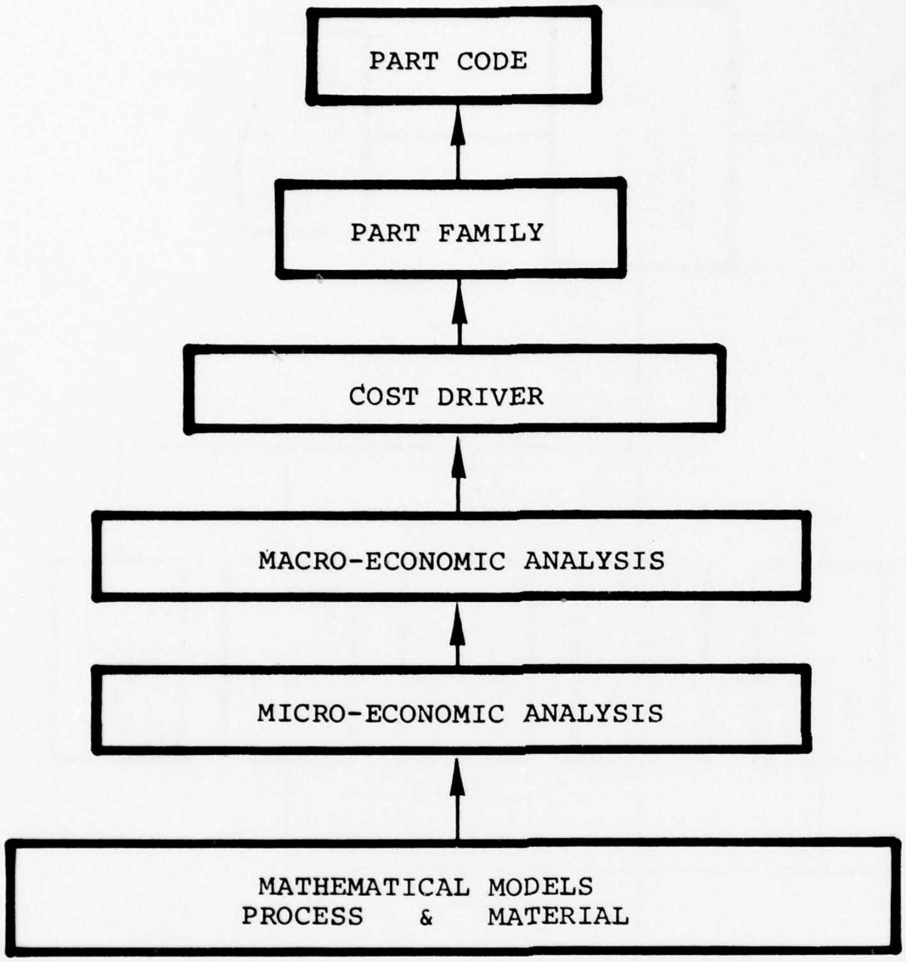


FIGURE 64 - INTERRELATIONSHIP BETWEEN MATHEMATICAL MODELS, MICRO- AND MACRO-ECONOMIC ANALYSIS, COST DRIVER, PART FAMILY AND PART CODE

AD-A053 339 METCUT RESEARCH ASSOCIATES INC CINCINNATI OHIO F/G 13/8
MATHEMATICAL MODELING OF MATERIAL REMOVAL PROCESSES FOR IMPROVE--ETC(U)
SEP 77 V A TIPNIS, S A VOGEL, S C BUESCHER F33615-76-C-5254
UNCLASSIFIED 1566-23599 AFML-TR-77-154 NL

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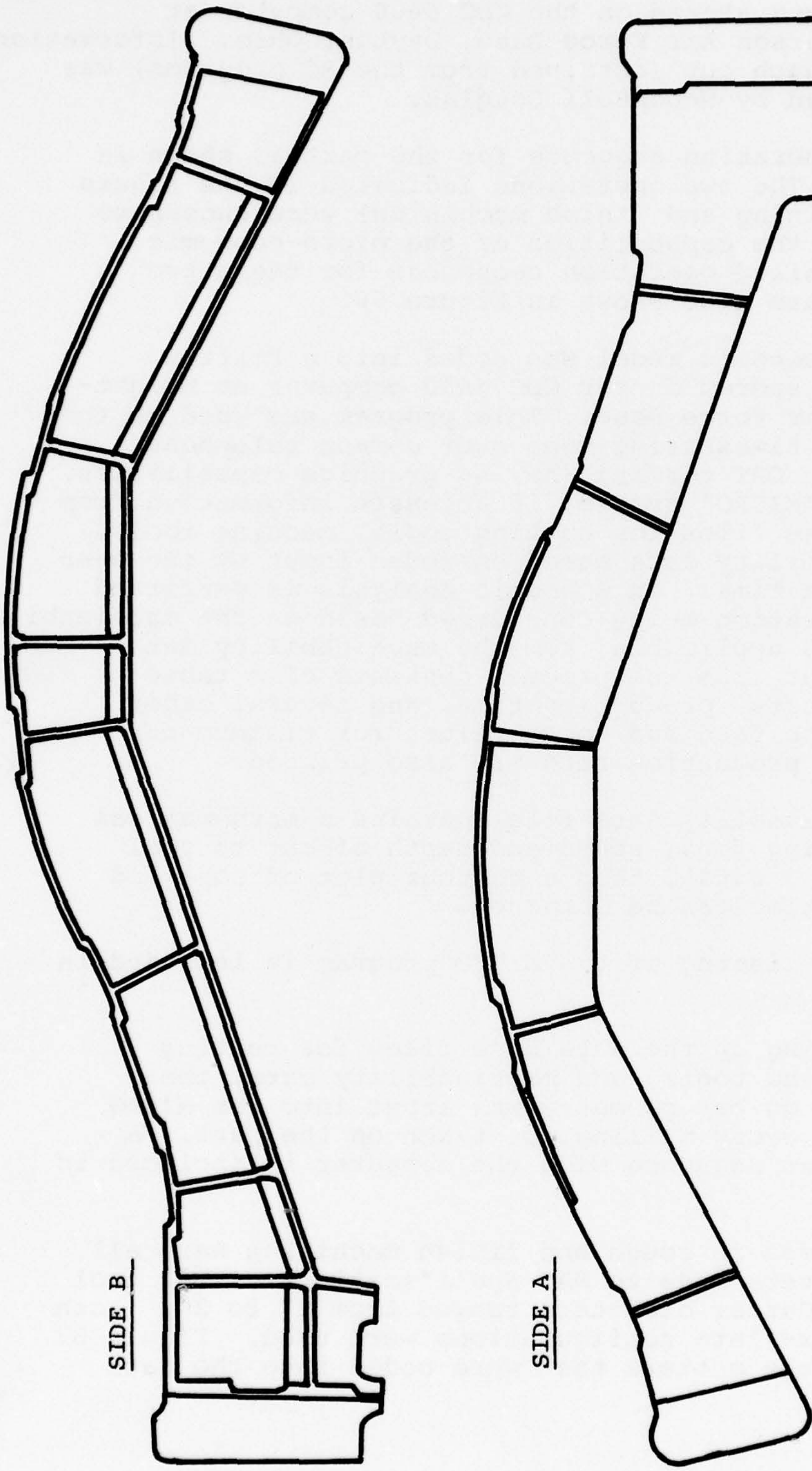


FIGURE 65 - PART DRAWING FOR MACRO/MICRO ANALYSIS OF F-15 FORMER-UPPER PANEL

base files and stored on the CDC 6600 computer at Wright-Patterson Air Force Base, Dayton, Ohio. Information describing each cut (obtained from the NC programs) was also provided by McDonnell Douglas.

The total operation sequence for the part is shown in Figure 66. The two operations indicated in the figure (rough machining and finish machining) were chosen to demonstrate the capabilities of the micro-economic model. Detailed operation sequences for these two operations are also shown in Figure 66.

The micro-economic model was coded into a Fortran program and stored on the CDC 6600 computer at Wright-Patterson Air Force Base. This program was used in the interactive timesharing mode over common telephone lines with a CRT terminal having graphics capabilities. Called the "MICRO" system, it accesses information from the data base files for cutting tools, machine tools, and machinability data based on codes input by the user at execution time. An economic analysis is performed for the operation being considered based on the machinability data that is applicable from the machinability data file. Output from the program consists of a table output of costs, production time, and several other outputs. The feed and speed values for minimum cost and maximum production rate are also printed.

If the machinabilty data file contains a mathematical model relating feed, speed and depth of cut to tool life (Level 3 data), then a contour plot of cost and production time can be obtained.

The Fortran listing of the MICRO program is included in Appendix E.

After building up the data base files for cutting tools, machine tools, and machinability data, the information on cut geometry was input into the MICRO program for every milling cut taken on the part. A typical input sequence with the computer is included in Appendix F.

The tools used in rough and finish machining were all milling cutters made to NAS Specifications of M42 tool material. Cutter diameters ranged from 1" to 2". Both four and six-flute configurations were used. Figure 67 summarizes the cutters that were coded into the data base.

OPERATION SEQUENCE FOR F-15 FORMER-UPPER PANEL

DESCRIPTION

Furnish Material

Rough Machine

Finish Machine

Inspect

Saw Tooling Lugs

Mill Corner Radii

Deburr

Inspect

Pickle

Package

Ship

Machine•3-Axis N/C Mill

Mill Tooling Surfaces - Side B
Rough Mill Rib Tops - Side A
Rough Mill Tooling Surfaces - Side A
Rough Mill Periphery - Side B
Rough Mill Pockets - Side B
Rough Mill Rib Tops - Side B

Machine•5-Axis N/C Mill

Fin. Mill Rib & Flange Tops - Side A
Fin. Mill Pocket Floors - Side A
Mill Tooling Pads - Side A
Fin. Mill Pocket Walls - Side A
Form Corner & Fillet Radii - Side A
Fin. Mill Flange Tops - Side B
Semi-Finish Periphery - Side B
Fin. Mill Periphery - Side B
Fin. Mill Rib & Flange Tops - Side B
Fin. Mill Periphery - Side B
Fin. Mill Radii - Side B
Fin. Mill Pocket Floors - Side B
Fin. Mill Pocket Walls - Side B
Fin. Mill Corner Radii - Side B

FIGURE 66 - PROCESS SHEET FOR F-15 FORMER-UPPER PANEL

Tool Code	Diameter (in.)	Flute Length (in.)	No. Flutes	Corner Radius (in.)	Condition
12410	1.00	2.00	4	B/N	Roughing
12420	1.00	2.00	4	.25	.06" Under
34241	0.75	2.00	4	.09	New
12141	0.50	1.00	4	.09	New
12430	1.00	2.00	4	.12	New
12440	1.00	2.00	4	B/N	.02" Under
12241	0.50	2.00	4	.09	New
22610	2.00	2.00	6	.12	Roughing
24610	2.00	4.00	6	.12	Roughing
15360	1.50	3.00	6	.19	Chip Breaker
14260	1.25	2.00	6	.12	New
14360	1.25	3.00	6	.12	New
14261	1.25	2.00	6	.09	New

FIGURE 67 - CUTTING TOOL LIFE FOR MICRO-ECONOMIC ANALYSIS OF F-15 FORMER-UPPER PANEL

Two machine tools were used for rough and finish machining the F-15 former. Roughing was performed on a 3-spindle Cincinnati 3-axis Medium N/C Profiler. Finish milling was performed on a 3-spindle Cincinnati 5-axis Double Gantry N/C Profiler. Information for these machine tools was obtained from McDonnell Douglas Aircraft Company and coded into the data base.

The amount of output from the MICRO program depends on what type of data is available in the machinability data file for the type of cut being taken. If only a starting recommendation of feed and speed is available (Level 1 data) then the output will consist of cost and time data at that feed and speed using three tool life values - the minimum expected tool life, maximum expected tool life and average expected tool life.

For the F-15 part, feed and speed values for every milling cut were obtained which would result in tool life values between 30 and 90 minutes. Therefore, the economics were computed assuming a tool life of 30, 60 and 90 minutes for each cut. The total output for each cut is shown in Appendix G.

A summary of all cuts taken on the F-15 former is given in Figure 68. Cost data is shown for each operation based on a tool life of 60 minutes. The numbers indicated that if the cutting tools were changed after 60 minutes of cutting time, the cost of the roughing and finishing operations would total \$538.64. Of this total, \$223.36 was attributable to roughing and \$315.28 was for finishing. The analysis also showed that the greatest cost for rough and finish machining was the tooling cost. The least expensive was constant cost (load-unload, setup, and rapid traverse). The average cost per cubic inch of metal removed was .10 \$/in.^{3} for roughing and 1.06 \$/in.^{3} for finishing.

Level 1 data provides an economic analysis based on starting recommendations of feed and speed for a particular cut. In order to optimize, however, tool life at various feeds and speeds must be used in the micro-economic model. This Level 2 data can be obtained from either controlled tool life experiments or from actual shop experience.

Cut No.	Cut Description	Side	Feeding Cost ($)	Tooling Cost ($)	Total Cost ($)	Volume of Metal Removed (in^3)	Cost of Material Removal ($\$/in^3$)
1	Mill Tooling Surfaces	B	21.24	60.50	81.74	900.09	0.09
2	Rough Mill Rib Tops	A	7.06	9.41	16.47	182.30	0.09
3	Rough Mill Tooling Surf.	A	14.83	41.30	56.13	712.09	0.08
4	Rough Mill Periphery	B	4.71	15.05	19.76	171.01	0.12
5	Rough Mill Pockets	B	9.29	20.00	29.29	405.72	0.07
6	Rough Mill Rib Tops	B	2.66	3.41	6.07	45.34	0.13
7	Finish Mill Rib & Flange Tops	A	6.37	8.43	14.80	11.84	1.25
8	Finish Mill Pocket Floors	A	19.85	30.16	50.01	771.46	0.06
9	Mill Tooling Pads	A	2.22	3.11	5.33	4.61	1.16
10	Finish Mill Pocket Walls	A	14.03	14.72	28.75	28.15	1.02
11	Form Corner & Fillet Radii	A	3.76	3.32	7.08	7.65	0.93
12	Fin. Mill Flange Tops	B	4.51	7.85	12.36	14.76	0.84
13	Semi-Finish Periphery	B	2.03	3.36	5.39	23.38	0.23
14	Finish Mill Periphery	B	1.99	3.28	5.27	3.60	1.46
15	Fin. Mill Rib & Flange Tops	B	8.42	9.94	18.36	16.67	1.10
16	Finish Mill Periphery	B	5.20	6.28	11.48	12.26	0.94
17	Finish Mill Radii	B	1.20	1.20	2.40	2.37	1.01
18	Finish Mill Pocket Floors	B	29.08	45.52	74.60	442.54	0.17
19	Finish Mill Pocket Walls	B	19.33	20.50	39.83	23.65	1.68
20	Finish Mill Corner Radii	B	15.99	13.76	29.75	10.18	2.92

Figure 68 - LEVEL 1 DATA FOR ALL ROUGH AND FINISH MILLING CUTS ASSUMING 60 MIN. TOOL LIFE FOR F-15 FORMER-UPPER PANEL

Level 2 data was obtained for one of the cuts taken for the F-15 former (Cut #16 - "Finish Mill Periphery - Side B"). Most of the data was obtained from the final report of a previous contract performed for the Air Force by Metcut Research (Contract No. F33615-74-C-5025). The results of the micro-economic model based on this data are summarized in Figure 69. To facilitate comparison of the Level 2 results with Level 1 results, the Level 1 information for this cut is included in the figure.

The Level 2 results showed that the cost of the operation could be reduced by using different values of feed and speed from those recommended for Level 1 data. Cost could be reduced from $11.67 (assuming the 60 minute tool life at .007 ipt feed and 52.4 fpm speed for Level 1 data) to $3.44 at .006 ipt feed and 150 fpm speed. It was interesting to note that the cost began to rise again when speed was increased to 200 fpm, even though the metal removal rate was higher. This was because more money was being spent on tooling, which more than offset the savings in cutting time.

If enough data is collected at various feeds and speeds for a particular cut (Level 2 data) it may be possible to create models which mathematically relate machining response (tool life, forces, surface finish, etc.) to the various process parameters (feed, speed, depth of cut, diameter of cutting tool). This is Level 3 data, and it allows for a precise optimization of cost and production time within the constraints such as machine tool limitations, force limitations, tool life limits, and surface finish requirements.

Cut No. 16 (Finish Mill Periphery - Side B) was selected to be analyzed using Level 3 machinability data. The mathematical model relating tool life and force to feed, speed and depth of cut for this workpiece material-cutting tool combination was obtained from data generated by Metcut in a previous contract (No. F33615-74-C-5025). The final form of the models for force and tool life is given in Figure 70.

	Feed (ipt)	Speed (fpm)	Tool Life (min.)	Cost ($)	Time (min.)	Volume Metal Removed (in^3)	Cost of Material Removal ($/in^3)
LEVEL 1 DATA	.007	52.4	30	17.94	26.2	12.26	1.46
	.007	52.4	60	11.67	25.1	12.26	0.95
	.007	52.4	90	9.58	24.7	12.26	0.78
LEVEL 2 DATA	.006	150.0	135	3.44	11.16	12.26	0.28
	.006	200.0	15	9.47	9.31	12.26	0.77

MIN. COST

MIN. TIME

FIGURE 69 - LEVEL 1 AND LEVEL 2 RESULTS FOR "FINISH MILL PERIPHERY - SIDE B"

$$\ln T = 27.9224 - 7.2153\,(\ln V) + 0.2912\,(\ln F)^2 + 0.9198\,(\ln RD)^2 + .3241\,(\ln F)\,(\ln AD) - .6007\,(\ln RD)\,(\ln AD)$$

$$\ln FR = 7.5269 - 4.2048\,(\ln RD) + .7691\,(\ln AD) + .3852\,(\ln AD)^2 - .2618\,(\ln RD)\,(\ln F) + .6569\,(\ln RD)\,(\ln V)$$

where:

- T = tool life
- FR = radial force
- V = cutting speed (fpm)
- F = feed (ipt)
- RD = radial depth (in.)
- AD = axial depth (in.)

NOTE: Tool life equation has been adjusted to result in 80% confidence model.

FIGURE 70 - MATHEMATICAL MODELS USED FOR LEVEL 3 DATA IN MICRO-ECONOMIC ANALYSIS OF F-15 FORMER-UPPER PANEL

Since tool life is described mathematically over a range of feed and speed for Level 3 data, the relationship can be substituted for tool life in the generalized economic equation in Section 3.5 . The cost and time are described mathematically over that range of feed and speed. This makes it possible to plot contour lines of constant cost and constant time within the boundaries of feed and speed, which is the main output from the micro-economic analysis using Level 3 machinability data.

Economics is not the only consideration in choosing feed and speed. There are constraints which must be met such as the force between the cutter and workpiece and the surface finish. The force is important in relation to tolerance since the cutter and workpiece deflect a certain amount during the cut. For example, a maximum force of 1000 lbs. might be established based on the tolerance of the feature being cut. This force is in the direction perpendicular to the motion of the cutter.

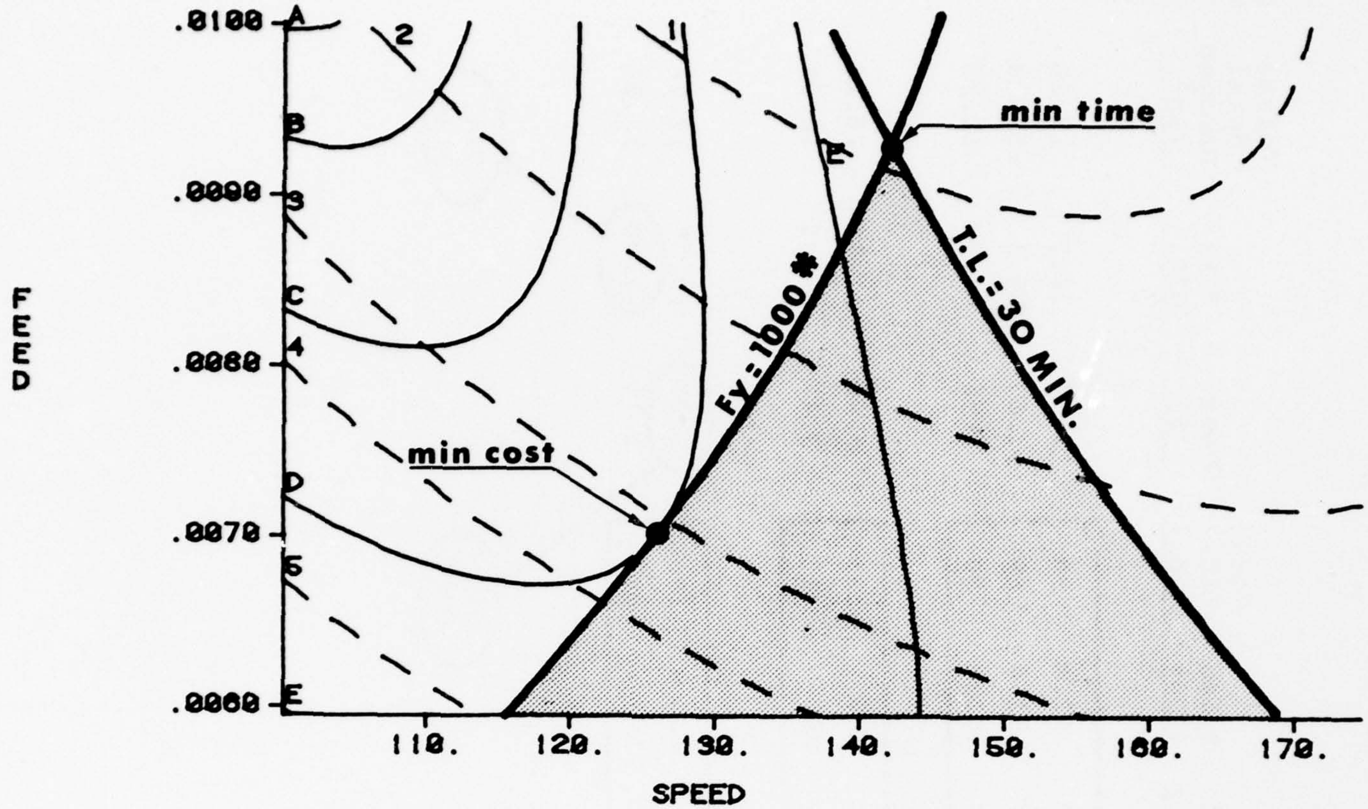
Another type of constraint is the minimum acceptable tool life. If an NC tape contains 30 minutes of cutting time, then the tool should run for at least 30 minutes before changing it. Thus, a minimum tool life of 30 minutes is established.

The constraints are plotted on the cost and time contour plot to define the acceptable working area of feed and speed. For Cut No. 16, this plot is shown in Figure 71. The force restriction and minimum tool life restriction are shown, and the acceptable working area is cross-hatched. Analysis of this figure shows a minimum cost of $3.00 at a feed rate of .007 ipt and a speed of 128 fpm.

It should be pointed out that the tool life model used in the preceding example was based on a lower confidence interval of 80%. In other words, it is 80% certain that the tool life value predicted by the model will be greater than or equal to the actual tool life.

Summary of Micro-Economic Analysis

To summarize the results of the micro-economic analysis of the F-15 Former-Upper Panel, Figure 72 shows the economic results from the MICRO program for all three levels of machinability data for Cut #16. This figure demonstrates the improvements in cost and production time that are attainable with more detailed machinability data for the selection of optimized machining parameters.



COST ($) - A= 2.40 B= 2.50 C= 2.70 D= 3.00 E= 3.50
PRODUCTION TIME (MIN) - 1= 8.00 2= 9.00 3= 10.50 4= 11.50 5= 13.50
MAX TOOL LIFE= 0.0 SOLID=COST DASHED=TIME

Figure 71 - COST AND PRODUCTION TIME CONTOURS FOR "FINISH MILL PERIPHERY-SIDE B" USING LEVEL 3 MACHINABILITY DATA

	Feed (ipt)	Speed (fpm)	Tool Life (min.)	Cost ($)	Time (min.)	Volume Metal Removed (in^3)	Cost of Material Removal ($\$/in^3$)
LEVEL 1 DATA	.007	52.4	30	17.94	26.2	12.26	1.46
	.007	52.4	60	11.67	25.1	12.26	0.95
	.007	52.4	90	9.58	24.7	12.26	0.78
LEVEL 2 DATA	.006	150	135	3.44	11.16	12.26	0.28
	.006	200	15	9.47	9.31	12.26	0.77
LEVEL 3 DATA	.007	128	143	3.00	10.75	12.26	0.24
	.009	143	32	3.75	7.90	12.26	0.31

MIN. COST

MIN. TIME

FIGURE 72 - LEVEL 1, LEVEL 2, AND LEVEL 3 RESULTS FOR "FINISH MILL PERIPHERY - SIDE B"

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

On the basis of the concepts investigated and the analysis and experiments performed, the following conclusions were drawn regarding the use of mathematical and economic modeling of material removal processes for improved process design, planning, optimization and control.

(1) The recommended approach for quantitative characterization of the material removal process is to develop mathematical relationships between the machining response (such as tool life) and the operating conditions(such as speed, feed, etc.) through a set of experiments. For the present, insufficient understanding of the machining phenomena forces us to employ the above empirical approach.

(2) In the past, the empirical approach has led to the development of deterministic, statistical, probabilistic, stochastic and dynamic mathematical models for material removal processes. Currently, the statistical and probabilistic approaches are undergoing further development, and the stochastic and dynamic models remain in their early stages.

(3) With regard to model development, certain facts were known about the major problem areas which were to be investigated. They were as follows: (a) Design of experiments: During statistically designed experiments, such as those using factorial, fractional-factorial composite and other designs, it is required that the position and levels of independent variables such as speed, feed and depth of cut be selected a priori. However, since the machining response such as tool life is not known a priori, often the preselected positions and ranges result in tool life that is too short hence impractical, or too long hence too expensive to investigate. A methodology was needed to establish the range of the practical tool life region and the machining response within this region when the knowledge of the location of the region itself was not likely to be available until a series of tests were completed.

(b) Shape of the Working Region: In material removal processing, the shape of the working region within which machining responses are of practical values is determined by the response itself as well as by the constraints imposed by the cutting tool, machine tool

and part design specifications. The definition of the region is extremely important to prevent unintentional or accidental extrapolation of the machining responses beyond the range of validity. Furthermore, the desirable operability region within the working region needs to be defined to obtain practical operating conditions based on a high degree of confidence (e.g., 95% of satisfying the constraints).

(c) Application of the mathematical models to aerospace production situations requires correlation between the laboratory tool life tests in which the speed, feed and depth are held at predetermined constant values during each individual tests and the typical numerical control and adaptive control airframe end milling cuts during which the radial depth, axial depth and feed are generally not constant.

(4) The concepts, approaches and experiments directed towards these major problem areas yielded:

(a) A recommended three-level methodology for producing mathematical models of material removal processes:

Stage I: Selection of an initial set of tests aimed primarily at obtaining a viable set of data to initiate Stage II.
Stage II: Selection and construction of process constraint models to define the feasible region for pre-production or production experimentation. Probabilistically defined constraints yield more realistic operating conditions based on a measured risk of violating constraints.
Stage III: Selection of additional machining tests aimed at experimental objective function optimization, namely, D-optimal criterion.

(b) A correlation between the laboratory tests and production performance indicating that the production conditions should be more conservative.The variability with work material, cutting tools and non-constant operating conditions as well as the desire to reduce the risk of failure can account for these conservative production conditions.

(5) The basic economic model for material removal processes proposed in this investigation can incorporate mathematical models for machining response, cut geometry and cutting rate. The form of this basic model is suitable for economic tradeoff analysis and optimization. This basic model can be used to construct a macro-economic model which is useful when only the cost driver relationships are known such as during cost estimation and preplanning, and a micro-economic model which is applicable when detailed information on cuts, times and costs are known such as during detailed planning.

(6) The micro-economic model is applicable to a detailed cost estimation of an F-15 airframe part, and demonstrates the potential for a 30% reduction in material removal costs (excluding setup, load, unload costs) during end milling through the optimization of speeds and feeds.

4.2 Recommendations

(1) The concepts and methodologies developed under this contract represent a first step towards the transformation of the aerospace manufacturing from an "experience-based" to a knowledge and data-based" industry. As such, they should be verified and validated in the aerospace production environment. Application to computer aided manufacturing programs appears to be especially promising.

(2) Future work should be directed towards the development of concepts and methodologies in the following areas:

(a) Material, M-F-T-W system, and empirical and phenomenological models for material removal and deformation processes.

(b) Economic models for the design/manufacturing cost interface through an extension of the macro- and micro-economic model.

(c) Development and verification of economic models for sheet metal processes within the scope of the objectives of the Integrated Computer Aided Manufacturing (ICAM) program.

APPENDIX A

TOOL LIFE MODELS

TABLE I

DETERMINISTIC TOOL LIFE MODELS

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Taylor (1907)	$VT^n = C$ n, C : constants	Economic analysis of single point cutting
Woxen (1932)	$V = (\frac{T'}{T})^n \quad c\,(q + q_o)$ C: constant T': constant (approx. 60 min.) q: chip equivalent q_o: constant	Chip equivalent concept
Gilbert (1950)	$VT^n = \frac{C}{S^e\,a^f}$ S: feed a: depth of cut n, e, f are coefficients	Application to machining economics when feed and depth of cut are included in the analysis.

TABLE I (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Kronenberg (1954)	$V = (\frac{T'}{T})\ c\ \frac{(a/S)^k}{(S/a)^l}$ a: depth of cut C: constant S: feed T': constant (approx. 60 min.)	To incorporate the effect of feed and depth of cut
Brewer and Rueda (1963)	$VT^n b_e^{\alpha} = \lambda$ b_e: equivalent chip thickness α: workpiece material exponent λ: constant	Development of a more succinct tool life relationship with increased range of applicability relative to Taylor's equation.
Numerous Investigators	$VT^{n_1} f^{n_2} d^{n_3} = C$ n_1, n_2, n_3, C: constants	A more generalized Taylor form to include the effect of feed and depth of cut on tool life

TABLE I (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Colding (1959) Wu (1964)	$\text{Log } T = b_0 + b_1 \text{ Log } V + b_2 \text{ Log } f + b_3 \text{ Log } d + b_{12} \text{ Log } V \cdot \text{Log } f + b_{13} \text{ Log } V \cdot \text{Log } d + b_{23} \text{ Log } f \cdot \text{Log } d + b_{11} (\text{Log } V)^2 + b_{22} (\text{Log } f)^2 + b_{33} (\text{Log } d)^2$	A more generalized model aimed at defining model form applicable to a wider range of cutting conditions. Employed to develop improved cutting conditions via response surface methodology.
Mathijsen (1965)	$V \ (C_4 + T) = C_5$ C_4: tool-work material constant C_5: measure of the boundry value of cutting speed as T approaches zero	Developed to account for the nonlinearity of tool life. Generally applicable over a wider range of conditions than Taylor's model.
Kronenberg (1969)	$(V + C_6) \ T^{\beta} = C_7$ C_6: constant for straightening the curve in Log-Log space	Developed to "straighten" the tool life curve in Log-Log space.

TABLE I (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Novak (1971)	$(V + C_6) \cdot T^{\beta} = C_9 \cdot b_e^{x}$ b_e = equivalent chip thickness	More general extension of Taylor's equation which includes the chip equivalent concept. This model has not been tested experimentally.
Gorki Auto - Soviet Union	$T = T_o \, e^{a} \, (1 - (1 - b \ln V/V_o)^{\frac{1}{2}})$ T_o : standard tool life V_o : cutting speed corresponding to the standard tool life	Universal tool life equation developed to model and predict tool life over a very wide range of cutting speeds.
Konig and DePiereux (1969)	$\text{Log } T = b_0 + b_1 V^{b2} + b_3 f^{b_4}$ $T = e\left(- \frac{K_v}{m} V^{m} - \frac{i_s}{n} S^{n} + C\right)$	Nonlinear model form developed to serve a wider range of cutting conditions. Nonlinear least squares algorithms required to estimate the parameters.

TABLE I (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Hirsch (1969)	$VT^n = S^e a^f VK^n C$ C, K: constants e, f, n are coefficients S, a, V are cutting variables	Nonlinear effects of speed, feed and depth of cut
Wu, Ermer, Hill (1966)	$E(T) = \beta_0 + \beta_1 V^{\alpha_1} + \beta_1 f^{\alpha_2} + \beta_3 d^{\alpha_3}$ $T^{(\lambda)}: \begin{cases} T^{\lambda} - 1 \big/ \left(\lambda (\dot{T})^{\lambda - 1}\right) & \lambda \neq 0 \\ \dot{T} \, LnT & \lambda = 0 \end{cases}$ $\dot{T}$ is the geometric mean λ = transformation parameter	A generalized set of transformations to overcome modeling difficulties when working with Taylor's model. Nonlinearities in tool life data may be better accounted for through the use of such power transformations.
Podurayeu and Yaroslavtsev	$T = Cto \big/ V_1^x \int_0^{t_o} \theta_p^y (t) \, d_t$ t_o: cutting time per cycle V_1: cutting speed during interrupted machining x, y: speed and temperature effect exponents C: constant $\theta_p(t)$: variable temperature at the tool-work contant	A tool life model for interrupted cutting applications

TABLE II

STATISTICAL TOOL LIFE MODELS

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Wu (1964) Response Surface Methodology Approach to Tool Life Testing	$\text{Log } T = Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2$ $X_1 = \text{Log } V,\ X_2 = \text{Log } f,\ X_3 = \text{Log } d$	Statistically designed experiments - center composite design - used to collect data. $100(1-\alpha)\%$ confidence intervals determined for $\hat{Y}$, $\hat{Y} \pm t_{v,1-\alpha/2}(\text{Var}(\hat{Y}))^{1/2}$ Analysis of variance performed to test the adequacy of the fitted second order model.
Wu, Ermer, Hill (1966) Study of Power Transformations in Tool Life Modeling	$E\left[T^{(\lambda)}\right] = \beta_0 + \beta_1 V^{\alpha_1} + \beta_2 f^{\alpha_2} + \beta_3 d^{\alpha_3}$ $T^{(\lambda)} = \begin{cases} T^{\lambda-1}/\lambda\ CT)^{\lambda} - 1 & \lambda \neq 0 \\ T\ \text{Ln}T & \lambda = 0 \end{cases}$	$100(1-\alpha)\%$ confidence regions for the parameters of the fitted tool life models and used to test the statistical significance of the transformation parameters. Confidence contour $= C_R =$ $\text{Ln Lmax}(\hat{\lambda}, \hat{\alpha}_1/Y, \hat{\alpha}_2) - 1/2\ X_v^2/n$ Ln Lmax is maximized Log likehood function of the parameters X_v^2-Chi square variable with v degrees of freedom.
Ermer & Wu (1967) Effect of experimental error on minimum cost economic analysis sensitivity	$\hat{Y} = \widehat{\text{Ln}T} = b_0 + b_1 \text{ Ln } V$	$100(1-\alpha)\%$ confidence intervals for the model parameters are established. $b_i \pm t_{v,1-\alpha/2}\ (S^2 a^{ii})^{1/2}$ S^2 = error variance, a^{ii} = the element of the i^{th} row and i^{th} column of the variance-covariance matrix. The range of parameter estimates defined by the statistical limits are used to define a statistical family of Taylor models then used to examine the cost function sensitivity to experimental errors.

TABLE II (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Iwata, et al (1972) Change-constrained programming used to develop a probabilistic economic optimization	$T = CV^{\alpha_1} f^{\alpha_2} W^{\alpha_3}$ W = flank wear at time, T	$100(1 - \alpha)$% confidence interfals are used to define statistical levels for the machining constraint equations to study their impact on the economic objective functions examined. The confidence intervals for the parameters α_1, α_2, and α_3 are used to define a family of statistical tool life models, $T_{.50}$, $T_{.90}$, $T_{.95}$, $T_{.99}$.
Wager and Barash (1971)	$f(T) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}(T - \bar{T})^2/\sigma^2}$ T = random variable tool life	The failure of high speed steel tools due to gradual wear is shown to be well represented by the normal distribution. Statistical analysis showed that the variation of tool life varied with the cutting conditions but was stabilized by the Log transformation.
Levi and Rossetto (1975)	$VT^n = C/\text{Ln } T = b_0 + b_1 \text{ Ln } V$	$100(1 - \alpha)$% joint confidence limits for the parameters of the fitted model were developed. $N(\beta_0 - b_0)^2 + 2(\beta_0 - b_0)(\beta_1 - b_1) \sum_{i=1}^{N} X_i + (\beta_1 - b_1)^2 \sum_{i=1}^{N} X_i^2 = 2 S_y^2 F_{2, N-2, 1-\alpha}$ Defines the elliptical confidence region/S_y^2 = Var (LnT)

TABLE II (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Friedman and Zlatin (1974)	$LnT = b_0 + b_1 \; Ln\,V$	Assume a normal distribution for tool life. Characterize the variation in tool life by the variance and the coefficient of variation. Discussion of the method of weighted least squares and the use of confidence intervals.
DeVor, Anderson, and Zdeblick (1976)	$LnT = b_0 + b_1 \; LnV + b_2 \; Lnf$ $(Ln\hat{T}_o) \pm t_{v,\; 1-\alpha/2} \; (X'_o \; (\underline{X'}\,\underline{X})^{-1} \; X_o \; \sigma^2)^{\frac{1}{2}}$ $(Ln\overline{T}_o) \pm t_{v,\; 1-\alpha/2} \; (\frac{1}{g} + X'_o \; (\underline{X}'\underline{X})^{-1} \; X_o \sigma^2)^{\frac{1}{2}}$	$100(1-\alpha)\%$ confidence intervals for the true mean tool life and $100\,(1-\alpha)\%$ prediction intervals are developed. $Var\,(\hat{Y}_o) = X^1_o \; (X^1 \; X)^{-1} \; X_o \; \sigma^2$ $Var\,(\bar{Y}_o) = (1/g + Var\,(\hat{Y}_o))\,\sigma^2$ A weighted least squares approach to tool life model fitting led to revised confidence intervals. Tool life modeled by variance over cutting conditions and by the coefficient of variation.
Tipnis & Friedman (1975)	$lnV = AlnF + B$ $lnT = \beta + \gamma \; (lnR) + \delta \; (lnR)^2$ Where A, B, β, γ and δ are functions of the coefficients of a second order logarithmic tool life model and cutting rate equation coefficients. R = cutting rate	Using second order logarithmic tool life models and cutting rate equations, R-T characteristic functions are defined in V-F and R-T space.

TABLE III

PROBABILISTIC TOOL LIFE MODELS

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Pas'Ko (1970)	$P_{ij}(t) = \text{EXP} \left\{ -\left(\frac{t}{\rho_{ij}}\right)^{\alpha_{ij}} \right\}$ i^{th} tool and j^{th} group, α_{ij} = scatter parameter, ρ_{ij} = tool life parameter, t = time measured in number of workpieces	For multi-tool setups, study the grouping of tools and the economic strategy for changing based on tool life scatter characteristics.
Wager and Barash (1971)	$f(T) = \frac{1}{\sqrt{2\pi}\,\sigma_T} \text{EXP} \left\{ -\frac{1}{2} \left(\frac{T - \overline{T}}{\sigma_T}\right)^2 \right\}$ T = tool life based on flank wear $\overline{T}$ = true mean tool life	Study of the probability disturbance aspects of tool life. The normal model was found to represent a good approximation, the flank wear failure characteristics of cutting tools
Rossetto and Levi (1976)	$F(T) = W_1 \left[1 - \text{EXP}(-\lambda T) \right] + (1 - W_1) \int_0^T \frac{\text{EXP}\left[-(\text{Ln}T - \mu)^2 / 2\sigma^2 \right]}{\sigma T \sqrt{2\pi}} dT$ T = tool life λ = failure rate W_1 = weighting constant μ = true mean tool life	Modeling of tool failure due to both gradual wear and fracture and impact of these failure mode characteristics on machining economics.

TABLE III (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Ramalingam (unpublished)	$f(t) = \frac{1}{\lambda} \text{ EXP } \left\{ - t/\lambda \right\}$	Model for catastrophic tool failure - random
	$f(t) = \frac{\beta t^{\beta - 1}}{\lambda^{\beta}} \text{ EXP } \left[- (\frac{t}{\lambda})^{\beta} \right]$	Model for catastrophic tool failure - time dependent
	$f_{x+y}(t) = \lambda^2 t e^{-\lambda t}$	Independent multiple chance failures
	$f(t) = \left\{ \frac{d}{dt} \cdot M(t) \right\} e^{-M(t)} \frac{[M(t)^{M-1}]}{(n-1)!}$	Model for time-dependent hazard functions and nonlinear tool wear
	λ = mean time to failure β = parameter M = mean value function	

TABLE IV

STOCHASTIC AND DYNAMIC MODELS IN MATERIAL REMOVAL PROCESSES

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
McAdams (1964)	$P_R \left\{ X_{t+1} = S_K / X_t = S_j,\ X_{t-1} = S_i \right\} \sim$ 2nd order Markov Chain Process where $f_{ij}(n) = P_{ij}(n) - \sum_{m-1}^{n-1} f_{ij}(m) P_{jj}(n-m)$ provides the first passage probabilities $f_{ij}(n)$ as a function of the passage probabilities $P_{ij}(n)$, i.e., probability of transition from state S_i to S_j in n transitions	Characterization of the surface profile (2-dimensional) of a grinding surface.
McAdams (1964)	$Yn = \alpha Y_{n-1} + \beta X_n$ $N = 1, 2, 3 \ldots$ Markov Chains $Yn = \alpha_1 Y_{n-1} + \alpha_2 Y_{n-2} + \beta Xn$ Single and double filtered gaussian noise Xn = white noise	Simulation and general profile characterization of abrasive belts
Peklenik (1964)	Introduces $\left\{P_k\right\} = \frac{1}{N-K} \sum_{d=1}^{N-k} (Z_d - \mu)(Z_{d+k} - \mu) \Big/ \frac{1}{N} \sum_{d=1}^{N} (Z_d - \mu)^2$, where $\left\{P_k\right\}$ is the correlation function of the time series Zd, d = 1, ..., n K = lag	Characterization of grinding wheel profiles; uses the correlation function to uniquely define the grain size, structure, hardness of the wheel

TABLE IV (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Peklenik (1967)	$\gamma_{xx}(k) = e^{-\alpha k}$; $\gamma_{xx}(k) = e^{-\alpha k} + \text{Cos}\,\Pi k$; $\gamma_{xx}(k) = e^{-\alpha k}\,\text{Cos}\,\Pi k$ $\gamma_{xx}(k)$ is the k^{th} Lag Autocorrelation coefficient of the time series X	Establish a surface typology based on the autocorrelation function; use of deterministic functions to represent various characteristic shapes of sample correlation functions.
Kubo (1967)	$P(w) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} A(X)\,\text{Cos}\,wXdx$ where $A(X) = \lim_{K \to \infty} \frac{1}{2K} \int_{-K}^{K} f(X)\,f(X + \Delta X)\,dX$ P (w) = power spectrum A (X) = correlation function of the time series X w = frequency	Characterization of various machined surfaced by both correlation theory and special analysis.
Ber and Braun (1968)	Power spectrum analysis via an electronic spectrum analyzer	Sample spectra examined for various machined surfaces to characterize the surface texture under varying machining conditions

TABLE IV (continued)

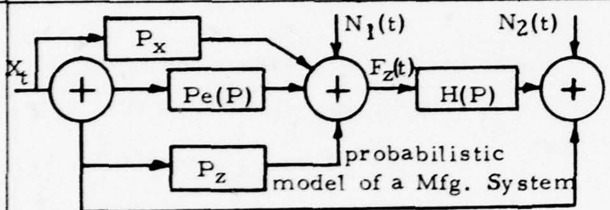
INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Yoshikawa & Sata (168)	An (X, Y, Z), (axial, peripheral, radial) coordinate system used to simulate abrasive grains, the position of which are defined by $X_i = \alpha R_{3i-2}$; $Y_i = Y_{i-1} + \beta \operatorname{Log}(R_{3i-1})$; $Z_i = \sqrt{R_{3i}}$ correlation and spectral density functions used to define the transfer function $\lvert S(f) \rvert = (P_o(f)/P_i(f))^{1/2}$ P_o = output spectrum, P_i = input spectrum	Simulation of the grinding process by Monte Carlo Method
Peklenik & Kwiatkowski (1967)	 Auto and cross - correlations and power spectra define the transfer functions	X_t = wave form of input surface Z_t = wave form of output surface P_x = chip thickness trans. function P_x = input trans. function P_z = output trans. function $F_z(t)$ = cutting force $N_1(t)$, $N_2(t)$ are disturbances $H(p)$ = machine structure transfer function
Kwiatkowski & Al-Samarai (1968)	$R_{fx}(t) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(t)\, X(t+\tau)\, dt$ - cross correlation of X_t, $f(t)$ $H(jw) = \int_{-\infty}^{+\infty} h(\lambda) e^{-jw\lambda}\, d_\lambda$ = frequency response function of the system, $h(\lambda)$ = impulse response function, $X(t)$ = system output, $f(t)$ = input (excitation)	Correlation and spectra functions used to develop a method for system identification in the milling process. Random component in cutting force used as structure excitation.

TABLE IV (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Stralkowski, Wu and DeVor (1969)	$Z_t = \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + a_t$ Z_t - time series, $a_t \sim NID(0, \sigma^2)$ 2nd order auto regressive, AR(2), model	characterization of the two-dimensional abrasive profiles of grinding wheels
Deutsch and Wu (1970)	$Z_t = \phi_1 Z_{t-1} + a_t$, $Z_t = a_t - \theta_1 a_{t-1}$ $Z_t = \phi_1 Z_{t-1} + \phi_2 Z_{t-2}$ 1st and 2nd order autoregressive and 1st order moving average models	Model the profiles of grinding wheels study of the sample interval and number of observations needed to adequately model and discriminate between various wheels
DeVor and Wu (1972)	$(1-B^S)(1-\phi_1 B) Z_t = (1-\theta_1 B)(1-\Theta_1 B^S) a_t$ B - backward shift operator, Z_t - surface *profile*, a_t - *white noise* seasonal autoregressive - moving average model	Model and characterize for interpretive purposes the texture of machined surfaces from the milling process

TABLE IV (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Wu and Dalal (1971)	$Y_t = Y_{t-1} + a_t - \theta_1 a_{t-1}$ - integrated moving average model IMA (0, 1, 1)	Model the observed deviations from the target of an automatic screw machine. Model used in the development of an optimum operating policy based on minimum expected cost/period
Deutsch and Wu (1973)	$Z_t = \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + \phi_3 Z_{t-3}$ AR (3)model $Z_t = \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + a_t$ AR (2) model	Model the profile of abrasive wheels; study the relative contribution of the wheel constituents to the profile topography
Peklenik, et al (1973)	$\lvert I(f) \rvert^2 = S_{F_y}(f) / S_{F_z}(f)$ F_y = output force time series F_z = input force time series S = power spectrum $\lvert I(f) \rvert^2$ = process transfer function	Study of the on-line identification of the cutting process. Sharp vs. worn tools are examined with respect to the cutting process with applications to adaptive control systems

TABLE IV (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Sata, et al (1973)	Power spectra $S_{x,y}$ (f) are examined for the cutting process. Total power, power of peak, frequency of peak employed	Identify cutting states with respect to four categories of chip formation and vibration-chatter
Moriwaki (1973)	$F(i) = \sum_{l=0}^{p} g(l)\,h(i-l) + n(i) \sim$ linear stochastic process, F (i) = process output; g (l) = impulse response function, h (i) = input as a moving average; n (i) = process noise, $n(i) = a_1 n(i-1) + a_2 n(i-2) + \ldots + a_q n(i-q) + r(i)$	Model the dynamic characteristics of the cutting process. Dynamic stiffness and cutting forces are measured and modeled
Law and Wu (1973)	$f(x) = 1/\alpha$; $f(\Delta Y) = \beta e^{-\beta(\Delta Y)}$; $f(z) = K + 1/\delta e^{K+1} (2^{K+1} - 1)\ (\delta e + Z)^K$ above eqs. used to simulate the grinding profile Sample spectrum $\bar{C}$ (f) determined for workpiece surface profiles based on the simulation X, Y, Z = three dimensional coordinate system	Simulation study of the grinding process. Study the grain - workpiece interactions during cutting

TABLE IV (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Law, Wu and Joglekar (1973)	f (x), f (ΔY), f (z) above used to simulate grinding profiles $\overline{C}(f) = 2\Delta\left\{C(o) \sum_{K=1}^{L-1} C(K)\, w(K) \cos \frac{\pi f K \Delta}{NF}\right\}$ $C(K) = \frac{1}{N} \sum_{1}^{N-K} (Y(t) - \overline{Y})(Y(t+K) - \overline{Y})$ w (K) = tukey lag window, Δ = sample interval, L = truncation Pt. for auto-covariances	Grinding process, modeled in terms of grain distributions and grinding conditions. Sample spectra used to estimate model parameters.
Pandit & Wu (1973)	$X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + a_t - \theta_1 a_{t-1}$ $\sim$ discrete ARMA (2, 1) process $\frac{d^2x(t)}{dt^2} + 2\zeta Wn \frac{dx(t)}{dt} + Wn^2 x(t) = Z(t)$ $\sim$ continuous 2nd order process Wn and Zeta are functions of ϕ_1, ϕ_2, θ_1	Show the relationship between a continuous process and its associated uniformly sampled discrete process. Model and interpret the abrasive wheel profile by this new continuous time series model.

TABLE IV (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Pandit, Subramanian & Wu (1975)	$\frac{d^{2n}X}{dt^n} + a_{2n-1}\frac{d^{2n-1}X}{dt^{2n-1}} + \ldots + a_oX = Z$ given eq. of order 2n for random vibration of chatter. $X_t - \phi_1 X_{t-1} - \phi_2 X_{t-2} - \ldots - \phi_{2n} X_{t-2n} = a_t - \theta_1 a_{t-1} - \ldots - \theta_{2n-1} a_{t-2n-1}$ Uniformly sampled autoregressive model of order 2n (USA (2n))	Machine tool chatter is studied as a self-excited vibration. Chatter is modeled by continuous time series models.
Pandit, Subramanian & Wu (1975)	$M\, d^2X/dt^2 + C\,dX/dt + KX = \alpha d^2X/dt^2 + \beta dX/dt + \gamma X + Z(t)$ $X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + a_t - \theta_1 a_{t-1}$	Self-excited random vibrations are studied to examine their static and dynamic stabilities. Purpose is to identify regions for machining operation.

TABLE V

MATHEMATICAL MODELS FOR MACHINING RESPONSES OTHER THAN TOOL LIFE

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Wu and Meyer (1964)	$\hat{Y} = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+ b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$ Y = Ln (cutting tool temperature), X_1 = LnV, X_2 = Lnf, X_3 = Lnd	Response surface methodology study to develop an equation to predict temperature of the cutting tool as a function of the cutting conditions
Wu and Meyer (1965)	$\hat{Y} = b_0+b_1X_1+b_2X_2+b_3X_3+b_4X_4+b_5X_5$ Y = Ln (cutting temp.), X_1 = LnV, X_2 = Lnf, X_3 = Lnd, X_4 = Ln (side cutting edge angle), X_5 = Ln (nose radius)	Develop a simple first order cutting tool temperature predicting equation based on both machine cutting conditions and tool geometry
Wu and Meyer (1967)	$\hat{d} = b_0+\sum_{i=1}^{2} b_iX_i+\sum_{i=1}^{2}\sum_{j=1}^{2} b_{ij}X_iX_j+\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} b_{ijk}X_iX_jX_k$ $\hat{d}$ = predicted crater depth, X_1, X_2 coordinates on rake face of tool	Model and predict the shape of the wear crater - predict crater volume

TABLE V (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Wu and Meyer (1967)	$\hat{Y} = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3+b_{123}X_1X_2X_3$ $\hat{Y}$ = predicted crater response (maximum depth, dimensions W_1, W_2 crater center, crater top surface area) X_1 = speed, X_2 = feed, X_3 = nose radius	Predict the size, shape, depth, etc. of crater wear on carbide tools as a function of speed, feed, geometry, main variable and interaction effects studied
Saxena and Wu (1969)	$\theta = b_1N^{b_2}f^{b_3}\left(1-\exp\left\{-(b_4N+b_5f+b_6Nf)\,t\right\}\right)$ θ = drill temperature, N = RPM, f = feed rate	Develop a transient drill temperature equation. Nonlinear model building techniques introduced to materials processing. Analysis of variance and confidence interval analysis is employed.
Mukherjee and Basu (1973)	$LnY = b_0+b_1Ln(V)+b_2Ln(f)+b_3Ln(d)+b_4Ln$ (work temp.) LnY - Ln of surface finish and tool life	Study the influence of workpiece surface temperature θ on tool life and surface finish for a single point turning process

TABLE V (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Lambert, Dudek and Williams (1967)	$F_c = (b_0+b_1V)(b_2+b_3\ \alpha)\ d^{b_4+b_5\alpha}f^{\ b_6+b_7d}$ $F_c \sim$ cutting force, V = speed, α = side-rake angle, f = feed, d = depth cut	Develop an equation to predict cutting force as a function of the machining conditions in turning
Taraman and Lambert (1974)	$LnR = b_0+b_1LnV+b_2Lnf+b_3Lnd$ LnR = Ln transformation of surface roughness in CLA units $LnR = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_3$ $+b_{23}X_2X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2$ $X_1 = LnV,\ X_2 = Lnf,\ X_3 = Lnd$	Develop first and second order equations to predict surface finish. Surface roughness contours were developed and used to increase MRR without degrading surface finish
Mukherjee and Basu (1967)	$LnW = b_0+b_1LnV+b_2Lnf+b_3Lnd+b_4LnT$ W = flank wear, T = cutting time	Employ the techniques of multiple regression to model tool wear as a function of cutting conditions and time

TABLE V (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Bhattacharyya, Faria-Gonzalez and Ham (1971)	$R_a = b_0 f^{b1}$ $R_a = b_0 f^{b1} V^{b2}$ $P = b_0 f^{b1} V^{b2}$ R_a = surface roughness in CLA units P = cutting power	Multiple regression techniques are used to develop models for power and surface finish which are employed as constraints in a machining optimization study
Williams and McGilchrist (1967)	$Ln(T_D) = b_0 + \sum_{i=1}^{4} b_i X_i + \sum_{i}^{4} \sum_{j \neq 1}^{4} b_{ij} X_i X_j \sum_{i}^{4} b_{ii} X_i^2$ T_D = drill life, $X_1 = LnV$, $X_2 = Lnf$, X_3 = Ln (point angle), X_4 = Ln (nom. relief angle)	Study the influence of cutting and drill design factors on drill life
Lambert and Taraman (1973)	$LnF = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2$ F = force, $X_1 = LnV$, $X_2 = Lnf$, $X_3 = Lnd$	Model and predict the forces in turning contours of constant force were developed and used to locate machining conditions which would increase MRR without increasing forces

TABLE V (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Rasch and Rolstadas (1971)	$R_a = b_0(b_1V)(b_2f)(b_3r)(b_4t)$ R_a = surface roughness r = nose radius t = cutting time	Develop a surface roughness constraint equation used in a machining optimization study
Petropoulos (1973)	$P_c = b_0V^{b1}f^{b2}$ P_c = cutting power (KW) $Ra = b_0V^{b1}f^{b2}$ R_a = surface roughness (CLA)	Develop constraint equations in an optimization of machining study by geometric programming
Walvekar and Lambert (1970)	$P = b_0V^{b1}f^{b2}$ P = cutting power $VT^{N1}f^{N2} = C$ $T^{N1}f^{N2}$	Develop constraint equation in an optimization study of machining conditions

TABLE V (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Draghici and Paltinea (1974)	Several power functions in speed, depth, cutting time, pitch feed, and other milling parameters. All models of the same form $Y = b_0 X_1^{b1} X_2^{b2} X_3^{b3} \ldots X_k^{bk}$	Study of process optimization in milling
Bedini, Lisini, Pinotti (1976)	Several power functions in feedrate, spindle speed, cutting velocity for bending on tool, spindle torque, cutting power	Study of adaptive control in milling
Iwata, et al (1972)	$F_c = b_0 V^{b1} f^{b2}$ - cutting force $T = b_0 V^{b1} f^{b2} d^{b3} t^{b4}$ - tool life	Turning economic optimization by chance - constrained programming

TABLE V (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Tipnis, Buescher & Garrison (1976)	$\ln(Y) = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$ $+ b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{44}X_4^2$ $+ b_{12}X_1X_2 + b_{13}X_1X_3 + b_{14}X_1X_4$ $+ b_{23}X_2X_3 + b_{24}X_2X_4 + b_{34}X_3X_4$ where Y = cutting force (X direction, Y direction or resultant) $X_1 = \ln f$ $X_2 = \ln V$ $X_3 = \ln AD$ $X_4 = \ln RD$	Stepwise multiple regression techniques used to build a model that can be of use in Adaptive Control.

TABLE VI

EXPERIMENTAL DESIGNS APPLIED TO MATERIAL REMOVAL PROCESSES

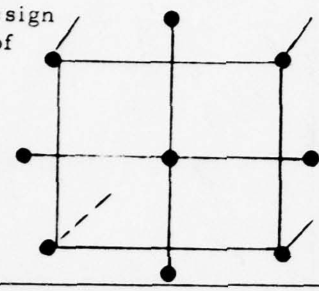
INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Wu (1964)	Central composite design (speed, feed, depth of cut) 18 test points (center points are replicated) 	Response surface methodology study of tool life testing concept of orthogonal blocking introduced
Wu and Meyer (1965)	Central composite design (speed, feed, depth of cut) 18 test points (replicated center points)	Response surface methodology study of cutting tool temperature prediction
Wu and Meyer (1965)	2^{5-1} fractional factorial design (speed, feed, depth of cut, size-cutting-edge angle, nose radius)	Develop a first-order cutting-tool temperature equation

TABLE VI (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Saxena and Wu (1969)	2^3 factorial plus $\lvert X'X \rvert$ selected tests (drilling speed and feedrate model-building plus best parameter estimation) $2^3 = 8$ tests	Build a non-linear drill temperature response equation
Wang, Taraman, Wu (1971)	2^{7-3} factional factorial design of resolution IV $2^{7-3} = 16$ tests	Study the main effects and 2-factor interaction effects of several die design factors on dishing, relative ban height, fracture angle and maximum force in punching
DeVries and Wu (1971)	2^8 full factorial design with replication $2^8 \times 2 = 512$ tests	Study the main and 2-factor interaction effects of 3 operating and 5 design factors on the steady-state drill temperature

TABLE VI (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Kuljanic (1973)	2^4 full factorial (feed/tooth, cutting speed, No. teeth, stiffness) Design was replicated to obtain estimate of error $2^4 \times 2 = 32$ tests	Study of milling process with particular emphasis on the effect of machine stiffness on wear
DeVor and Wu (1971)	2^3 full factorial (speed, feedrate, depth of cut in milling)	Study the effect of machining conditions on the surface finish as modeled by autoregressive - moving average models
Mukherjee and Basu (1973)	2^4 full factorial (speed, feed, depth of cut, work temperature)	Study effects of surface temperature on machining

TABLE VI (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Taraman and Lambert (1974)	Central composite design (speed, feed, depth of cut) 2^3 + star + center pts + replication (4 blocks of 6 tests each = 24 tests)	Develop a 2^{nd} order polynomial model to predict cutting surface finish
Lambert and Taraman (1973)	Central composite design (speed, feed, depth of cut) 2^3 + star+ center pts + replication (4 blocks of 6 tests each = 24 tests)	Develop a 2^{nd} order polynomial model to predict cutting forces in turning
Williams and McGilchrist (1967)	Central composite design (speed, feed, pt. angle, nom. relief angle) 2^4 + star (8) + center pts (25 tests points)	Drill life study

TABLE VI (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Zakaria and El-Gomayel	2^3 full factorial (speed, feed, depth of cut)	Study the relationship between tool temperature and tool life for adaptive control
Fujii et al (1972)	2^5 full factorial (plus replication)	Evaluate the effects of cutting conditions and drill grinding parameters on torque and thrust in drilling
Troitskaya and Gromyko (1974)	4 x 2 x 2 factorial design (speed x feed x depth of cut)	Model tool life by a 2^{nd} order polynomial in log transformed coordinates

TABLE VI (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Zohdi (1974)	2 x 3 x 5 x 3 x 2 full factorial (coolant x depth of cut x table speed x cross feed x grain size in split plot design arrangement 2 x 5 x 3 x 3 = 90 for each grain size - 3 replicates = 90 · 2 · 3 = 540	Statistical analysis and optimization of surface finish in grinding
Vaidyanathan (1969)	7 x 5 full factorial (speed x feed in drilling)	develop an equation to predict drill temperature and drill life
Micheletti, Boer and Vilenchich (1973)	3 - level factorial (speed, feed) $3^2 = 9$ tests	Response surface methodology study of tool life - economic optimization

TABLE VII

ECONOMIC MODELS AND METHODS OF ANALYSES FOR MATERIAL REMOVAL PROCESSES

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
F. W. Taylor (1900)	Cutting time = f (machining time, tool change time, setup time). Expression for maximum production rate as a function of speed.	This relationship was used to obtain speed at which production rate is maximum. Taylor's Tool Life Model was used for this purpose.
Ernst & Field (1946)	Cost = f (milling cost, initial cutter cost of cutter and cutter preparation cost, constant cost). Production Time = f (milling time, cutter change time, constant time).	This technique lead to quantitative cost analysis showing effects on cost and production rate of feed, speed, number of cutter teeth, lot size, load and unload time, etc. Graphic optimization of cost and production was conducted during actual production.
Gilbert (1950)	Cost = f (turning cost, initial cutter and cutter preparation cost, constant cost). Production Time = f (turning time, cutter change time, constant time).	This relationship was used to obtain speed at which cost is minimized and production rate is maximized. Taylor's Tool Life Model was used.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Brewer (1958)	Total cost/Pc = idle cost/Pc + tool changing cost/Pc + cutting cost/Pc + tool regrinding cost/Pc + tool depreciation cost/Pc + premature failure cost/Pc. Based on $VT^n f^\alpha d^\beta = \lambda$ for a tool life relationship	The objective of this study is to more carefully lay down in quantitative terms an economic model for metal cutting. The model should include at least the fundamental variables in the analysis.
Brown (1962)	Total cost/Pc= part handling cost/Pc+ cutting cost/Pc+ worn tool replacement cost/Pc + worn tool reconditioning cost/Pc. Specific models developed for: (i) single tool cutting in one pass, (ii) single tool cutting in two passes, (iii) multi-tool machining. The premature failure of tools is studied by employing a mobability model for tool wear based on the normal distribution and its use in determining the mobability of failure before the tool life is reached.	The objective of this study is to present some general relations for the selection of speed, feed and depth of cut to achieve optimum economic machining conditions. The analysis is based on the use of the power law to relate the machining variables to tool life and cutting power.
Brewer & Rueda (1963)	Total cost/Pc= setup and idle cost/Pc + machining cost/Pc+ tool changing cost/Pc + tool grinding cost/Pc+ tool depreciation cost/Pc. Based on modified Taylor T.L. Equation employing equivalent chip thickness $VT^n be^m = C$; optimum conditions subject to power constraint nomograms developed for practical application.	Development of a simplified method through the use of nomograms to select the most economical machining conditions. Study is over a broad range of ferrous and non-ferrous materials including difficult to machine alloys.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Brewer (1966)	Cost/Pc = setup and idle cost/Pc + machining cost/Pc + tool changing cost/Pc + tool grinding cost/Pc + tool depreciation cost/Pc. Based on equivalent chip thickness Taylor T. L. Model; surface finish constraints are introduced for finish cut economic analysis. Tool geometry is introduced into the economic analysis via the equivalent chip thickness which takes feed, depth of cut, side cutting edge angle and nose radius. There, feed is considered as a variable to be optimized. Maximum feed and power constraints are included.	The study attempts to more closely formulate the machining economics problem to optimize both speed and feed simultaneously in the face of various machining constraints.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Wu & Ermer (1966)	Profit= revenue - cost - find machining conditions which maximize profit revenue= (selling price)(volume), assuming linear demand function, selling price= a-b (volume); cost= fixed+ variable, cost= F+G (volume), max. profit occurs when marginal revenue= marginal cost	Formulate the machining economics problem by maximum profit concepts. Relationship of maximum profit cutting speed with minimum cost and maximum production rate speeds is shown.
Rice (1966)	Maximum profit conditions found from Max. $\left\{R(Y) - \text{Min. } C(X_i, \ldots X_n) \text{ subject to } y = f(X_i, \ldots X_n)\right\}$, R= revenue, C= cost function, f= production function (physical), Y= measured physical output, $X_i, \ldots X_n$=input control variables. A profit response surface in terms of the input variables is optimized via response surface methodology. Linear cost and production functions are employed.	Development of an experimental method from profit maximization based on Box and Wilson's method of RSM.
Matthijsen (1965)	Cost/Pc = cutting cost/Pc+ tool changing cost/Pc+ tool cost/Pc. This study examines the traditional minimum cost analysis by using a modified Taylor T.L. Eq. V(a+T)=C. The purpose is to recognize and account for the fact that T.L. does not follow a linear relation in Log-Log coordinates in many cases.	Study of the economic aspects of high cutting speeds and short tool lives and the use of a modified Taylor model to obtain more realistic results.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Armarego & Russell (1967)	$\frac{\text{Cost}}{\text{Pc.}}$ = (idle + handling cost) + (machining cost) + (tool changing cost) + (tool cost) $\frac{\text{Time}}{\text{Pc.}}$ = (idle+handling time)+ machining+ tool changing time. $\frac{\text{Profit}}{\text{Pc.}} = \frac{\text{income/Pc.} - \text{cost/Pc}}{\text{Time/Pc.}}$ $TV^{n1}f^{n2}d^{n3} = C$ used for tool life model	Analysis of single pass shaping and milling processes based on a maximum profit rate criterion.
Okushima & Fujii (1969)	Total production cost = $\frac{\text{machining cost}}{\text{Pc.}}$ x No Pcs. + cost for tools for each spindle to make P parts + cost for tool changes for each spindle to make P parts (unexpected)+ cost for changes for each spindle to make P parts (scheduled changes). Machining cost/Pc = cutting cost + handling cost + material cost	Study of determining the tool change interval which minimizes the total production cost for multi-spindle machine tools. The inherent variability of tool life is taken into consideration by using a probability distribution for tool life. Monte Carlo Simulation is used to solve the problem.
Ravignani (1969)	Simple cost and production rate models cost = cost of machining + cost of tooling time = machining time + handling time + tool changing time	Development of simplified graphical methods for determining optimal machining conditions.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Colding (1969)	Use of turning, milling, grinding, drilling chip equivalents to succinctly describe the cutting parameters. Tool life expressed in a productivity model, i.e., productivity = $p = ps\left(\frac{T}{T+Tv}\right)$. ps= velocity/chip equivalent (q) T= tool life, Tv= tool changing time+ tool re-grind time, 1/p - production cost, graphical analysis, q= chip equivalent= f(nose radius, depth of cut, side cutting edge angle)	Development of a simple economic model based on the chip equivalent concept to optimize the machining parameters.
Field, etal (1969)	Cost= f(feeding cost, rapid traverse cost, handling cost, setup cost, tool changing cost, tool holder, depreciation cost, tool cutter cost). Taylor Tool Life model used minimum cost cutting speeds determined based on models for turning, milling, drilling, reaming and tapping. Several different types of tooling are considered. Cost = (5 machine tool-related costs + 5 cutter-related costs)	Detailed cost and production rate models are developed and solved by the computer for optimum cutting conditions. Several processes and types of tooling are considered. Practical applications are stressed. Computer analysis is employed.
Walvekar & Lambert (1969)	Cost = machining cost + handling cost + tool changing cost + tool cost. $T = C^{1/n} V^{-1/n} f^{-a/n} \rightarrow$ solve for optimal V, f by geometric programming. Introduce power, surface finish constraints and solve by geometric programming.	Introduction of the use of geometric programming in solving the constrained machining economics problem.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Bartalucci, Bedini & Lisini (1969)	Detailed cost model which includes the basic terms (i) handling cost, (ii) cutting cost, (iii) tool cost, (iv) tool changing cost and in addition, machine tool depreciation cost, capital investment interest cost, energy cost and maintenance of machine tool cost. Power is used as a measure of the machine tool type available for the job.	Cost model developed which does not assume a given machine tool but rather includes machine tool-related costs in the model. Determination of optimal machine tool and optimal cutting parameters included in a more general model.
Ermer (1970)	Basic cost model = cost = f(machining cost + tool cost + tool changing cost + handling cost). Model tool wear (flank wear) as a linear function of time $W = b_0+b_1t+E$ assume the model parameters b_0, b_1 are normally distributed. Use the concepts of Bayesian Statistical Theory to develop the posterior dist$^{\underline{n}}$ of b_0, b_1 given their prior distribution and sample wear data based on Taylor's model, the cost model and the Bayesian wear model, cutting conditions for minimum cost are continually updated as new sample data comes to light. Posterior Density Function = $f(B/A)$ $$\frac{\underset{f(A/B)}{\text{(conditional dist}^{\underline{n}}\text{ of the sample information)}}\ \underset{f(B)}{\text{(prior dist}^{\underline{n}})}}{f(A/B)\ f(B)dB}$$	Formulation of a new approach to minimum cost analysis in machining based on a Bayesian model for tool wear. Formulation and numerical example is based on the turning process.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Ermer (1971)	Cost= machining cost+ tooling cost+ constant cost. Examine optimal machining parameter identification in the face of various cutting constraints; maximum horsepower available constraint, maximum allowable surface finish, maximum allowable feed rate. Optimal solution found by geometric programming.	Application of geometric programming to the determination of optimal machining conditions in turning.
Kops (1971)	Traditional cost model (machining cost, handling cost, tool cost, tool changing cost) is used as a basis to develop a cost model for turning parts with several steps. Two uses are examined (i) constant cutting velocity over all steps, (ii) constant RPM over all steps. Taylor T. L. model is employed. Constant speed method requires an added cost term due to the necessity of changing RPM for each step.	Economic (cost) aspects of cutting speed selection when machining stepped parts on a lathe.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Barash & Berra (1971)	Maximum production rate model developed for complex parts with many different diameters (steps). n operations are planned by computer analysis. Time = $\sum^{n}$ machining time + $\sum^{n}$ approach (rapid traverse) time + handling + tool changing. Optimization is subject to several constraints: tool failure during cut constraint, horsepower and surface finish constraint, tool life constraint. Based on a Kronnenberg tool life model $d^{z-g} T_L{}^y V F^{(g+z)} = \frac{C_V 60^y}{5^g (1000)^z}$	Automatic computer-based process planning for complex machining operations. Development of a computer algorithm to select the machining parameters subject to several machining constraints.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Hitomi (1971)	Develop an economics model for multi-stage machining - several distinct machines in sequence to produce a part. At each stage handling + machining + tool changing times are considered. A waiting time is introduced as well based on the assumption that no in-process inventory is allowed. Machine depreciation and other indirect costs are included in the ensuing cost model. Profit as a criterion is also considered. Problem is formulated as a general constrained optimization problem.	Mathematical model is developed to study the economic machine parameter selection problem in multi-stage machining systems. A computer program algorithm was developed to determine the optimal parameters.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Iwata, et al (1972)	In the economic analysis (i) volume of metal removed and (ii) production cost are used as objective functions. $Hv = \frac{\text{volume metal removed}}{\text{unit tool wear}} = \frac{CVfdt}{V_B \text{ (flank wear)}}$ where $t = 10^{\alpha 1} V^{\alpha 2} f^{\alpha 3} V_B^{\alpha 4}$ is the flank wear model. Traditional cost model is used; constraints used are (i) max. cutting speed, (ii) min. cutting speed, (iii) max. feed, (iv) min. feed, (v) max. cutting force, (vi) max. power consumption, (vii) stability region for cutting (no chatter), (viii) max. surface roughness. Both deterministic and stochastic constraints are present optimization done by chance-constrained programming methods.	A probabilistic approach to the constrained machining optimization problem is introduced based on the theory of chance-constrained programming. The stochastic nature of several constraints is shown to have a significant effect on the optimal cost and metal removal rate cutting conditions.
Kegg (1971)	Traditional cost model for turning with Taylor model for tool life is employed. Analysis here is aimed at assessing the penalty cost incurred when deviation from the true optimum occurs due to uncertainty in cutting data. A penalty cost function is determined by mathematical analysis of the production cost by a Taylor series expension about the deterministic optimum.	Selection of cutting speeds for minimum cost production when uncertainty in the cutting data is considered.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Micheletti, Boer & Vilenchich (1973)	Machining cost and production rate optimization approach via statistical modeling. Statistical models for tool life are employed and Monte Carlo simulation coupled with response surface methodology is used to identify the optimal cutting conditions through actual machining experiments.	Computer-optimization of costs and production rates in milling based on statistical design of experiments and model building.
Ermer & Shah (1973)	Cost and production rate models for milling, drilling, reaming and tapping are developed. Sensitivity of the optimum to Taylor's tool life model is examined.	Sensitivity analysis in optimum machining is studied.
Petropoulos (1973)	Traditional cost model (Brewer and others) together with Taylor's model used to formulate the cost optimization problem in turning. Power surface roughness, forces and speed, feed constraints are used. Primal and dual solutions are formulated and solved by geometric programming.	Optimal selection of machining parameters in a constrained cost model by geometric programming.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Muransky (1974)	Machining cost = machine cost + tool replacement time-cost + tool cost determine the optimal value of the tool life criterion to produce minimum cost when using throw-away inserts. $\Delta = C_o t^x$ = flank wear Δ_o = optimal value	Optimum tool life wear criterion for throw-away insert tools.
Draghici & Paltinea (1974)	Cost = machining cost + cost of changing a worn tool. Formulate the cost optimization problem in milling. Cost = f(cutter dia., cutting velocity, depth of cut, IPM, no. teeth) Power function used for tool life model T = f(speed, feed, depth of cut)	Use of convex mathematical programming in determining optimal machining parameters in milling.
Tipnis & Friedman (1976)	R=cutting rate= $f(V, f)$ T=tool life= $f(V, f)$ $\frac{\delta R}{\delta f} \Big/ \frac{\delta R}{\delta V} = \frac{\delta T}{\delta f} \Big/ \frac{\delta T}{\delta V}$ for every point on the R-T characteristic curve. R-T characteristic curve defined by the tangent points between lines of constant cutting rate and tool life. Economic optimum lies on the R-T curve.	Introduction of the concept of cutting rate - tool life characteristic curves for the determination of optimal machining parameters.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Claycombe & Sullivan (1976)	N= no. parts produced/day α 1/cutting time+ handling time+ tool changing time, C_{μ} = cost/part= direct machine cost+ indirect machine cost+ tool cost+ material cost. Profit= P= $(S-C_{\mu})^N$ / P(X)= profit= f(speed, feed, depth of cut) Assume 2nd order polynomial for P(X). Use of RSM to optimize profit	Use of response surface methodology to maximize profit experimentally.
Boothroyd & Rusek (1976)	Profit= (selling price-cost) / production time rate Cost= C= f(machine cost, handling cost, tool cost, tool changing cost). Solve for tool life for maximum rate of profit. Consideration given to the effect on profit rate of operator incentives which reduce production time.	Study of maximum profit rate as a machining criterion. Examination of the effect of operator incentives.
Hati & Rao (1976)	Cost and production rate models examined both deterministically and probabilistically. Objective functions and constraints are typical of many previous studies. A temperature constraint is introduced $\theta = CV^{B_1}f^{B_2}d^{B_3}$ as well as a depth of cut constraint. The objective function is formulated via a Taylor series of random variables, $F(X)=F(\overline{X}) + \sum \frac{\delta F}{\delta X_i} \Big/ \frac{(X_i-\overline{X}_i)}{\overline{x}}$ subject to similar probabilistic constraints.	Deterministic and stochastic examination of the constrained machining optimization problem.

TABLE VII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Buescher, Vogel & Tipnis (1976)	Cost = f (feeding cost, rapid traverse cost, handling cost, setup cost, tool changing cost, tool cutter cost).	Detailed cost and production rate models are solved by programmable calculators for optimum cutting conditions. Also, a post processor for optimizing feeds and speeds on NC tapes is introduced.

TABLE VIII

OPTIMIZATION OF COST, PRODUCTION RATE, AND PROFIT RATE

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Box (1960)	General process optimization problems	Statistical methods of design of experiments, statistical model building, response surface methodology and evolutionary operations
Berra & Barash (1968)	Minimize the total production time for an automatic turning process. The inputs to the problem are: 1) Part configuration and machine(s) requirements, 2) Machine parameters and raw material, and tool data	An iterative computer solution based on a heuristic approach in selecting "initial solutions"
Walvekar & Lambert (1970)	Minimum cost cutting speed and feed selection for a basic turning operation given operational restrictions. Horsepower and surface finish constraints are used	Geometric programming was used to formulate the problem. For non-linear optimization, the geometric programming technique is similar to the dual-problem approach for linear optimization. The optimal contribution of the constraints to the objective function is computed first, then the variable settings

TABLE VIII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Bhattacharyya & Ham (1970)	Minimum cost turning model with 1) surface finish and 2) horsepower constraints. Discrete speed (RPM) and feed (IPR) values are available	Lagrangian Multiplier Method of optimization with a iterative computer solution
Bartalucci, Bedini & Lisini (1970)	Minimum cost operating condition selection for automatic lathe: Multiple pass-no constraints	Dynamic program formulation solved by computer routine. Reduces problem to stages (passes) and solves for optimal decision at each stage
D.J. White (1971)	General process optimization	Review of a variety of standard optimization techniques with industrial applications

TABLE VIII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Ermer (1971)	Minimum cost turning model with operational constraints	Geometric programming formulation with additional insights into optimum solution and sensitivity analysis
J. Szadkowski	Overall production sequence optimization-minimum cost and time	Network formulation with solution based on Bellman's optimality principle
Hitomi (1971)	Multi-stage machining system optimization for flow-type production: Max. production, min. cost, max. profit	Stage-wise optimization with ordinary calculus and heuristic procedures for selecting overall optimum

TABLE VIII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Rasch & Rolstadas (1971)	Optimal speed and feed selection for finish turning: Discrete variable values	A discrete, non-convex search routine based on "isoproducts" is developed. Similar to a "cutting-plane" type integer programming solution
Iwata, Murotsu, Iwatsubo and Fujii (1972)	Optimal machining selection with probabilistic objective function and constraints	Presents the "chance-constrained programming" solution. Transforms the probabilistic problem into a deterministic equivalent
Mangasrian (1972)	Techniques of optimization	A review of non-linear optimization and search techniques

TABLE VIII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Petropoulos (1973)	Optimal cutting condition selection for constrained regions	Geometric programming approach
Ramaswamy & Lambert (1974)	Cost minimization for single-pass turning with inventory and penalty costs	Calculus and graphical solution
Drăghici & Păltînea (1974)	Cylindrical milling cutting condition selection with various operation constraints: 1) Max. rate, 2) force & torque of machine, 3) horsepower, 4) rigidity, 5) max. feed, 6) thermal stability of cutter, 7) depth of cut, 8) cutter wear and others	Solves unconstrained problem using classical method. Formulates constrained problem as a general non-linear optimization problem

TABLE VIII (continued)

INVESTIGATION	MODEL FORM	CONTEXT IN WHICH MODEL WAS DEVELOPED AND/OR USED
Pappas & Moradi (1975)	General non-linear search algorithm	Introduces and compares a new direct search algorithm
Tipnis, Field, & Friedman (1975)	Selection of optimal machining parameters for minimum cost and maximum production rate	Uses concept of R-T characteristic function for simultaneous optimization of multiple variables.
Hati & Rao (1976)	Optimal machining conditions determination with constraints; deterministic and probabilistic	The "sumt" computer routine was used to solve the problems. This method is based on solving a sequence of unconstrained problems.

APPENDIX B

PROBABILISTIC TOOL LIFE MODELS

I. Types of Tool Life Models:

<u>Deterministic</u> - The earliest method of model development based on postulating model forms that "fit" the observed tool life behavior or are based on metallurgical and physical properties. Examples: Taylor's model, Colding's model, the "chip equivalent" models, etc.

<u>Statistical</u> - Evolved with the realization of large tool life scatter. The model forms have been generally the previously developed deterministic forms, but have employed statistical inference and model building techniques to account for the inherent uncertainty in tool life.

<u>Probabilistic</u> - With the increasing acceptance that metal cutting processes are stochastic in nature, models developed which used various probability distributions to describe tool life. Standard reliability analysis methods are used, and the wear and failure mechanism is considered as a stochastic process.

II. Advantages of Probabilistic Models:

They convey the uncertainty inherent in tool life by associating it with a probability distribution.

Economic models developed take into account the risk associated with premature tool failure.

Tool life models developed are derived from fundamental principles of wear and failure mechanisms.

The modeling approach opens up a different view of the tool life phenomenon and stimulates further interest in investigating tool life.

III. Disadvantages of Probabilistic Models:

The incorporation of machining conditions such as speed, feed and depth of cut is not easily accomplished.

IV. Previous Studies Involving Probabilistic Tool Life Models:

<u>Brewer (1958)</u>

Studied the economics of the basic turning operation.

Specifically examined the nature of the tool wearland in the economic situation.

Developed relations for determining the size of the wearland for lowest cost based on the probability of premature failure of a tool before it is to be resharpened.

Based conclusions on two questionable assumptions: (1) That the probability of failure is proportional to the wearland value used as criterion of tool life raised to a fixed power; (2) The ratio of the cutting times of tools failing prematurely to those not failing prematurely is constant.

Employed tool life distribution data by Burmester (1951).

<u>Brown (1958)</u>

Discussed the selection of economical machining rates for single point tools removing material in one and two passes, and for operations involving more than one tool.

Used a generally deterministic economic model.

Took a probabilistic view of premature tool failure in estimating the cost of tool replacement.

Assumed a normal distribution for tool failure, that is, the probability of a tool failing completely at any time, t, is:

$$f(t) = (1/\sigma \sqrt{2\pi} \text{ EXP} \left[-\frac{1}{2} (t - T_u)^2/\sigma^2 \right]$$

where T_u = average time to complete failure, σ = standard deviation of tools failing under the particular cutting conditions.

The probability of a tool failing before its resharpening time, T_w, is

$$F\ (T_w) = \int_0^{T_w} f\ (t)\ dt$$

The mean cutting time of tools which fail prematurely, T_m, is

$$T_m = T_u - \left[\sigma f(T_{w_1})/F(T_{w_1}) \right]$$

which could be calculated simply from statistical tables for the normal distribution.

The comparison with Brewer's (1958) and Burmester's work is favorable for proper selection of T_u and σ.

Author stated that the statistical approach would be more favorable since it is based on more rational assumptions and can be calculated simply, even though the goodness-of-fit for the normal distribution has not been confirmed.

Wager and Barash (1970)

Studied the distributional aspects of HSS tools.

Stated that past research failed to mention the inherent uncertainty in tool life data, and proposed that this variation should be incorporated in economic models.

Stressed that the results for HSS tools do not necessarily hold true for carbide and ceramic tools.

Performed accelerated tool life tests under constant cutting conditions.

Examined the coefficient of variation ($K = S/\bar{X}$) and found it to be large and approximately constant at 0.30.

Compared the results obtained from Soysal (1966) and found them to be approximately equal.

Showed that the distribution of tool failure is adequately represented by the normal distribution, confirming Brown's assumption.

Called for a probabilistic definition of tool life, such as its being a predetermined probability of failure, rather than defining it through a series of actual tool life tests.

Pas'ko (1970)

Discussed the optimization of multitool setups while considering tool life scatter.

Considered setups of N tools joined into M groups each with N_j tools, i.e., $N = \sum N_j$.

Characterized each tool by a reliability function,

$$P_{ij}(t) = \text{EXP}\left[-(t/P_{ij})^{\alpha_{ij}}\right]$$

where j = # of group; i = # of tools in group, α_{ij} = scatter parameter, and P_{ij} = parameter which is defined through $\bar{T}_{ij}$ as

$$P_{ij} = T_{ij}/T \quad (1 + 1/\alpha_{ij})$$

t = time in # of workpieces.

The reliability function of a tool group is $P_j(t) = P_{1j}(t), P_{2j}(t) \ldots P_{njj}(t)$ can be presented by a Weibull distribution.

Developed economic models based on the reliability of tools in a group. The optimal was found as regards the number of workpieces/tool change using the Weibull distribution.

Iwata, Murotso, Iwatsubo, Fujii (1972)

Discussed the complete probabilistic approach to the determination of optimal cutting conditions by considering the uncertain nature both of an economic objective function and of constraints.

Used an optimization technique, "chance-constrained programming".

Used two separate objective functions: (1) volume of material removed per unit of tool wear; (2) production cost per component.

Used numerous machine tool, part, and machine tool dynamics constraints as follows:

Force = $KV^{\alpha_1} f^{\alpha_2}$

Power = $Fc \cdot V/6120\ \eta$ η = mech. efficiency

Roughness = $f^2/8 \cdot R$ R = nose radius

Defined the constrained region using different probability levels for the constraints.

Stated that different probability levels yield different optimal cutting conditions.

Assumed Normal distribution for the confidence intervals proposed.

Friedman and Zlatin (1974)

Discussed the variability of tool life as a function of the mean tool life.

Discussed the variance stabilization effect of the logrithmic transformation.

Stated that if the coefficient of variation is constant then the variance of Log(T) is constant (stabilized) over different cutting conditions (mean tool lives).

Assumed a Normal distribution of tool life.

Showed the coefficient of variation to be approximated by the standard deviation of Log(T) if the assumption of constant variance is true.

Reported that constant variance is not the case in tougher machining operations.

Suggested the weighted least squares method of modeling for the non-constant variance situation.

Ermer (1970)

Employed a Bayesian model for machining economics for optimization by adaptive control.

Assumed on-line measurement of tool wear is possible.

Assumed normal prior distribution for the wear parameters, linear tool wear and constant process variance.

Designed the "learning" model to incorporate periodic sampled data "on-line" and adjust the optimum accordingly.

Used basic turning and the minimum cost objective to illustrate the approach.

Used a logrighmic transformed Taylor tool life model.

Ran preliminary tool life tests to estimate C and n in Taylor's model and then V_{min} and T_{min}. As the process was run at V_{min}, the wear was measured and the parameters were re-evaluated.

Gave a simulated numerical example based on the above assumptions.

Levi and Rossetto (1975)

Analyzed the effect of tool life scatter on the uncertainty of the tool life parameters using the joint confidence region approach.

Used Taylor's logrithmic tool life model and assumed the errors to be Normal.

Developed the 95% joint confidence region for both b_0-b_1 and N-C showing the large uncertainty in the parameters. For example, N ranged from 100 to .34 and C from 52 to 88.

Discussed the large number tests required to obtain reasonable variance estimates.

Hati and Rao (1976)

Formulated a general economic problem with constraints for both a deterministic and probabilistic model.

Assumed all random variables to be Normal.

The problem had three dependent variables, speed, feed and depth of cut.

Used a computer technique, SUMT, to optimize the problem.

Converted the probabilistic model to a deterministic model to be solved.

Used a Taylor series expansion in two terms to yield a deterministic model.

$$F_1 = a_1\bar{\psi} + a_2\sigma\psi^2$$

from the probabilistic model.

$\bar{\psi}$ is the mean of the Taylor expansion of the objective function or constraint (assumed to be normal)
$\sigma\psi^2$ is the variance of ψ.
a_1 and a_2 are arbitrary constants which relate the importance of $\bar{\psi}$ and $\sigma\psi^2$.

Concluded that the production rate is higher for the deterministic case.

Kendall and Sheikh (1976)

Developed a tool replacement strategy for multi-tool machines using a probabilistic model and reliability techniques.

The probability that a tool fails before T (prematurely) is $F(T) = \int f(t)dt = 1 - R(T)$ where $f(t)$ = pdf of failure times for tools and $R(T)$ = reliability function for tools.

The cost of replacement is given by

$$C = C_F\left[(1 - R(T)\right] + C_p\left[(R(T)\right]$$

where C_F = cost of unplanned tool changes; C_p = cost of planned tool changes assumed that $C_p < C_F$.

The selection of the appropriate reliability function depends on the failure mode or modes. Multiple modes of failure (wear and premature) can be described by a single pdf, such as a mixed pdf.

$$f(t) = pf_1(t) + qf_2(t)$$

$$F(T) = pF_1(T) + qF_2(T)$$

$$R(T) = pR_1(T) + qR_2(T)$$

where $f_1(t)$ is the pdf for premature failure; $f_2(t)$ is the pdf for wear-out failure; p and q are weighting parameters where q + p = 1.

The Weibull distribution is given as a general failure distribution that can be adapted to various failure modes by the parameters:

a = scale parameter
b = shape parameter
d = location parameter

$$f(t) = ab(t-d)^{(b-1)} \exp\left[(-a(t-d)^b)\right]$$

$$F(T) = 1 - \exp\left[(-a(t-d)^b)\right]$$

$$R(T) = \exp\left[(-a(t-d)^b)\right]$$

The optimal replacement interval T* is obtained by differentiating the cost function with respect to T.

The problem of estimating the Weibull parameters is discussed for the tool wear situation.

<u>Rossetto and Levi (1975)</u>

Investigated the effect of the fracture and wear failure modes on stochastic tool life models and machining economics.

Many failure modes can be combined into one failure probability density function (pdf)

$$f(t) = \sum_{i=1}^{n} w_i f_i(t)$$

$$\sum_{i=1}^{n} w_i = 1$$

where $f_i(t)$ = pdf of i^{th} failure mode; w_i = weight of i^{th} failure mode.

Fracture or breakage failure mode can be characterized by a constant hazard function which results in an exponential pdf.

The gradual wear failure mode is represented by the normal pdf.

The overall cumulative distribution function (CDF) is

$$F(t) = w_i \left[1 - EXP(-\lambda t)\right] + (1-w_i) \int (\sigma t \sqrt{2\pi})^{-1}$$

$$EXP \left[-(lnt-u)^2/2\sigma^2\right] dt$$

The expected life of the tool, E(T), is a decreasing function of (= failure rate)

$$E(t) = 1/\lambda \left\{1 - \int (\sigma t \sqrt{2\pi})^{-1} \; EXP\left[(-\lambda t - (lnT-u)^2/2\sigma^2\right] dt\right\}$$

Practical use of the model requires estimates of μ, σ, λ and η and C (for Taylor's model).

Suggested that sequential experimentation right on the shop floor may provide a means to obtain parameter estimates.

Used the E(T) in the normal min-cost, max.-prod. max profit models in place of function T f(V,F) and solved for $T_{optimal}$.

Ramalingam and Watson (1976), and Ramalingam (1976)

Presented a hazard function which was defined through conditional probabilities and was equivalent to the hazard function found in reliability engineering

$$H(t) = f(t)/1-P(t)$$

Assumed a constant hazard function for a tool subject to chipping and fracture failure. The corresponding pdf for a constant hazard function was the exponential function

$$f(t) = 1/\lambda \exp(-t/\lambda)$$
$$F(t) = 1-\exp(-t/\lambda)$$

where $1/\lambda$ = constand hazard rate

Presented the increasing hazard function case, and for a linear hazard function and the quadratic hazard functions the pdf was the Weibull distribution

$$f(t) = \beta t^{\beta-1}/\lambda^{\beta} \quad \text{EXP} \left[-(t/\lambda)^{\beta} \right]$$

Multiple failure modes can be combined (if independent) by the sum of hazard functions

$$Zn\ (t) = \sum_{i=1}^{n} Z_i\ (t)$$

and

$$f(t) = Zn\ (t) \cdot \text{EXP} \left[- \int_0^t Zn(t)dt \right]$$

Developed a multiple-injury model by considering each injury to remove a volume of material δ from the tool. N such injuries result in a tool failure.

The pdf for the multiple-injury model is the gamma function, which for large N is approximated by a normal distribution.

$$f(t) = 1/\sqrt{2\pi\sigma^2} \quad \text{EXP} \left[-(x-u)^2/2\sigma^2 \right]$$

where $\mu = n/\lambda$; and $\sigma^2 = n/\lambda^2$

Gave a nonlinear wear example with a hazard function $\lambda(t) = \lambda(c/1 + t)$; $c > 0$. This yielded a gamma pdf for failure which can be approximated by the log-normal distribution.

v. Summary:

Studies into the probabilistic nature of tool failure have characterized the tool life distribution as Normal Weibull and gamma.

The distributions have been from various tool failure modes giving different hazard functions which yield the probability distribution functions.

The normal distribution had been shown by repetitious testing to adequately represent tool failure times.

The direct introduction of cutting conditions into the tool failure distributions has been attempted with respect to solving for the "optimal" tool life through an economic model and finding the cutting conditions through a deterministic tool life mode, i.e., Taylor's model.

APPENDIX C

REVIEW OF REGRESSION ANALYSIS NOMENCLATURE AND RELATIONSHIPS

a) Homogeneous Variance Case

For the linear model of the form

$$y_i = f(\underline{x}_i, \underline{b}) + \epsilon_i \qquad (A1)$$

or in matrix form

$$\underline{Y} = \underline{Xb} + \underline{\epsilon} \qquad (A2)$$

where y_i is the observed response for the i^{th} test

$\underline{x}_i = (x_{1i}, x_{2i}, \ldots, x_{pi})$ is the (1 x p) vector of independent variables for the i^{th} test.

ϵ_i is the error for the i^{th} test, assumed $NID(0, \sigma_i^2)$

$\underline{Y} = [y_1, y_2, \ldots, y_N]^T$ is the (N x 1) vector of observed responses

$\underline{X} = [x_1^T \; x_2^T \; \ldots \; x_N^T]^T$ is the (N x P) matrix of independent variables

$\underline{\epsilon} = [\epsilon_1, \epsilon_2, \ldots, \epsilon_N]^T$ is the error matrix assumed to have equal variance, i.e. $Var(\underline{\epsilon}) = \underline{I}\,\sigma^2$

$\underline{b} = [b_1, b_2, \ldots, b_p]^T$ is the (p x 1) vector of model parameters.

The least squares estimates of the parameters $\underline{b}$ of the linear model are given by

$$\hat{\underline{b}} = (\underline{X}^T\underline{X})^{-1}\underline{X}^T\underline{Y} \qquad (A3)$$

and

$$Var(\hat{\underline{b}}) = (\underline{X}^T\underline{X})^{-1}\,\hat{\sigma}^2 \qquad (A4)$$

$$Var(\hat{y}_o) = \underline{x}_o(\underline{X}^T\underline{X})\underline{x}_o^T\hat{\sigma}^2 \qquad (A5)$$

$$Var(\bar{y}_o) = Var(\hat{y}_o) + \hat{\sigma}^2/g \qquad (A6)$$

where $\hat{y}_o = \underline{x}_o\hat{\underline{b}}$ is the predicted true mean response, and $\bar{y}_o = \hat{y}_o$ is the predicted mean of g future observations.

b) Inhomogeneous Variance (Weighted Least Squares) Case

When the assumption of equality of variance is not justified, i.e. var ($\underline{\epsilon}$) = $\underline{V}\sigma^2$ where $\underline{V}$ is the variance - covariance matrix of the independent observations,

$$\underline{V} = \begin{bmatrix} \sigma_1^2 & & & & 0 \\ & \sigma_2^2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ 0 & & & & \cdot \\ & & & & \sigma_N^2 \end{bmatrix} \tag{A7}$$

The weighted least squares estimates of the parameters $\underline{b}$ are given by

$$\hat{\underline{b}} = (\underline{X}^T\underline{V}^{-1}\underline{X})^{-1}\underline{X}^T\underline{V}^{-1}\underline{Y} \tag{A8}$$

and

$$\text{Var}(\hat{\underline{b}}) = (\underline{X}^T\underline{V}^{-1}\underline{X})^{-1}\hat{\sigma}_w^2 \tag{A9}$$

$$\text{Var}(\hat{Y}_\circ) = \underline{x}_\circ \; (\underline{X}^T\underline{V}^{-1}\underline{X})^{-1}\underline{x}_\circ^T\hat{\sigma}_w^2 \tag{A10}$$

$$\text{Var}(\overline{Y}_\circ) = \text{VAR}(\hat{Y}_\circ) + \hat{\sigma}_\circ^2/g \tag{A11}$$

where $\hat{\sigma}_\circ^2$ is the variance of y at $\underline{x}_\circ$ and $\hat{\sigma}_w^2$ is the weighted mean square of the residuals of the fitted model.

APPENDIX D

J. Tlusty (1), P. MacNeil, McMaster University, Hamilton, Canada

Summary: End milling is a basic operation in contouring and die sinking controlled by copying or NC or by Adaptive Control. The feed rate in these operations must often be set with respect to the deflection or strength of the cutter. In Adaptive Control these may be the control parameters. For all these purposes the knowledge of the cutting force is important and, especially of its dynamics. The paper explains and gives data on the variation of the cutting force at constant depth and width of cut as well as in transients like that of cutter entering the side of the workpiece. For the latter the rather fast increase of force amplitude is demonstrated. Further on it is shown that the force responds to a change in feed rate with a time delay which may cause instability in the Adaptive Control loop.

INTRODUCTION

End milling is a very typical operation in Copy or NC controlled contour and die sinking operations. In many of these cases the cutting force is an important parameter with respect to either the deflection of the cutter or its breakage. It is especially important in Adaptive Control where it may be used as the control parameter. The transfer function between table velocity $\underline{s}$ (feed rate) and the cutting force $\underline{F}$ is a part of the AC feedback loop. It is then especially the dynamics of the transfer function $\underline{F/s}$ which affects the behaviour of the system.

There are three aspects of this dynamics: the variation of the cutting force in a steady state of constant depth and width of cut, in the transients (e.g. entry of the cutter into the workpiece) and the time delay included in this transfer function.

However, the knowledge of the magnitude and variation of the cutting force as dependent on the conditions of the cut is essential also for the programming of conventional NC or Copy milling operations. Since Piekenbrink's work [1] there has not been to our knowledge, any publication about cutting forces in milling and his own work was concerned with face milling and steady state only. In end milling due to the comparatively longer tooth edge engaged in the cut and smaller number of teeth even the steady state may considerably differ from that in face milling. The information given in this paper is based both on computed and experimentally obtained data. For computing, a rather simple formula for the tangential cutting force on a part of one tooth is assumed:

$$F_t = K\, b\, h, \tag{1}$$

where $\underline{b}$ is the width of the cut, measured parallel to the axis of the cutter, and $\underline{h}$ is the chip thickness; $\underline{K}$ is a constant dependent on the material of the workpiece and on the geometry of the tool as well as on the average chip thickness. For values of the "specific force" K, see e.g. [2]. The radial component of the cutting force is assumed $F_r = 0.3\, F_t$.

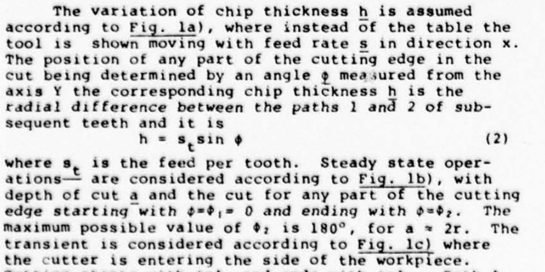


FIG.1

The variation of chip thickness $\underline{h}$ is assumed according to Fig. 1a), where instead of the table the tool is shown moving with feed rate $\underline{s}$ in direction x. The position of any part of the cutting edge in the cut being determined by an angle ϕ measured from the axis Y the corresponding chip thickness $\underline{h}$ is the radial difference between the paths 1 and 2 of subsequent teeth and it is

$$h = s_t \sin\phi \tag{2}$$

where s_t is the feed per tooth. Steady state operations are considered according to Fig. 1b), with depth of cut $\underline{a}$ and the cut for any part of the cutting edge starting with $\phi = \Phi_1 = 0$ and ending with $\phi = \Phi_2$. The maximum possible value of Φ_2 is 180°, for $a = 2r$. The transient is considered according to Fig. 1c) where the cutter is entering the side of the workpiece. Cutting starts with $\phi = \Phi_1$ and ends with $\phi = \Phi_2$. Both Φ_1 and Φ_2 vary during the transient but there is always $\Phi_1 = 180° - \Phi_2$.

STEADY STATE

In deriving the formulae for the variation of the magnitude of the total radial force acting on the cutter we shall consider a case as in Fig. 2a). An end milling cutter is used with a helix angle $\underline{\beta}$. The depth of cut is $\underline{a}$, the width of cut is $\underline{b}$. A right hand helix is used and the teeth which are cutting are at the back of the plan view as indicated by broken lines. In Fig. 2b) the action of one tooth is considered on a plan which shows the unfolded (unrolled) surface of the cut. The cutting edge is then a straight line inclined by β and it moves from left to right. Three successive positions 1,2,3 of the moving edge are indicated. Any such position is measured by the angle α (shown for position 2) through which the leading point of the cutting edge has moved from the beginning of its cutting action. (For correct dimensional representation the horizontal distances in the plan view are obtained by multiplying the given angles by the value of cutter radius r). In the position 2 the total length of the edge engaged in the cut is $r\delta = b \tan\beta$ and the angular positions ϕ of the individual points of the edge spread from $(\alpha-\delta)$ to α. The whole action may be divided into three phases. In phase A the length of the cutting edge increases from 0 to the maximum width b (to the engagement angle δ). In phase B the length of cutting edge remains constant while it moves through varying chip thickness. In phase C the cutting edge length gradually decreases. The ranges of α are:

$$A\!: [0,\delta],\ B\!: [\delta,\Phi_2];\ C\ [\Phi_2,\ \Phi_2+\delta] \tag{3}$$

For a large ratio of cut width $\underline{b}$ to cut depth $\underline{a}$ the cycle is slightly different from the just described one which we denote Type I. In the Type II cycle shown in Fig. 2C) the engagement angle of the cutting edge reaches at the end of phase A a value Φ_2 which is smaller than $\delta = b \tan\beta / r$. Throughout phase B the cut spreads constantly over a range of $0<\phi<\Phi_2$. As is shown later, this causes the force to remain constant in this phase. The ranges for α are now:

$$A\!: [0,\Phi_2];\ B\!: [\Phi_2,\delta];\ C\!: [\delta,\ \Phi_2+\delta] \tag{4}$$

In any position of the cutting edge during the cut the cutting force is distributed non uniformly along the edge because its individual points have different angular positions ϕ and, consequently, they cut different chip thicknesses. This is illustrated in Fig. 3. Using Eqs(1) and (2), the contribution of an element $\underline{dy}$ of the cutting edge to the total cutting force is:

$$dF_t = K\, s_t \sin\phi\, dy \tag{5}$$

$$dF_r = 0.3\, K\, s_t \sin\phi\, dy$$

The resulting force element $\underline{dF}$ when applied at the center of the cutter may be decomposed into fixed directions X and Y:

$$\begin{aligned} dF_x &= -dF_t\cos\phi - dF_r\sin\phi = -Ks_t(\sin\phi\cos\phi + 0.3\sin^2\phi)dy \\ dF_y &= dF_t\sin\phi - dF_r\cos\phi = Ks_t(\sin^2\phi - 0.3\sin\phi\cos\phi)dy \end{aligned} \tag{6}$$

Using:

$$dy = \frac{r}{\tan\beta}\, d\phi, \tag{7}$$

we may integrate expressions (6) within the limits of ϕ in the individual phases of the cycles:

$$\begin{aligned} &\text{Type I. A: } [0,\alpha],\ \text{B: } [\alpha-\delta,\alpha],\ \text{C: } [\alpha-\delta,\Phi_2] \\ &\text{Type II. A: } [0,\alpha],\ \text{B: } [0,\Phi_2],\ \text{C: } [\alpha-\delta,\Phi_2] \end{aligned} \tag{8}$$

Thus, the limits are the same for Type I and Type II in phases A and C; they differ in phases B. Carrying out the integrations and denoting as a unit force F_u:

$$F_u = 0.5K\, s_t \frac{r}{\tan\beta} \tag{9}$$

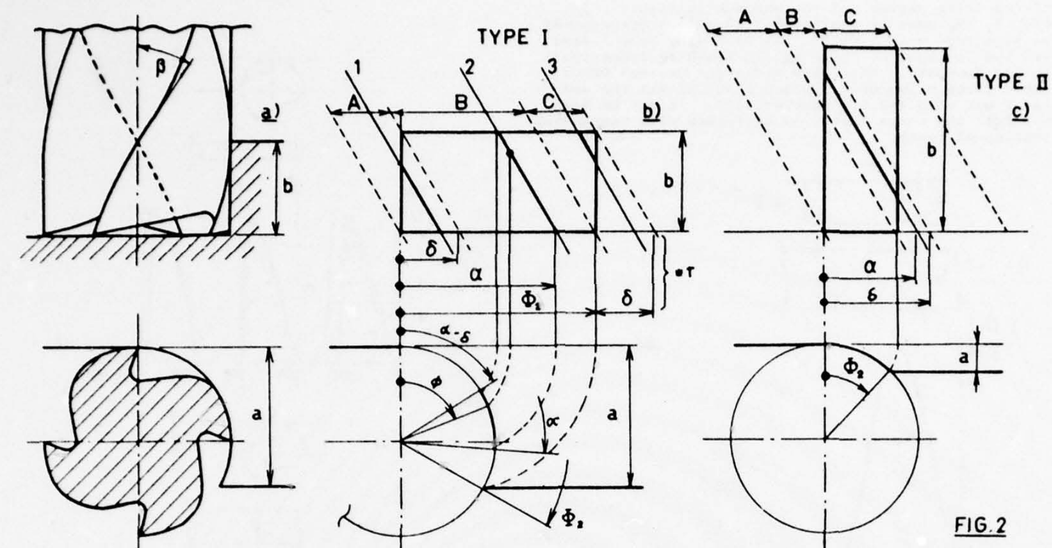


FIG.2

it is obtained:

Phase A:

$$F_x = -F_u(\sin^2\alpha - 0.15\sin 2\alpha + 0.3\alpha)$$

$$F_y = F_u(\alpha - 0.5\sin 2\alpha - 0.3\sin^2\alpha)$$

Phase B,I:

$$F_x = -F_u[\sin^2\alpha - \sin^2(\alpha-\delta) + 0.3\delta + 0.15\sin 2(\alpha-\delta) - 0.15\sin 2\alpha]$$

$$F_y = F_u[\delta - 0.5\sin 2\alpha + 0.5\sin 2(\alpha-\delta) - 0.3\sin^2\alpha + 0.3\sin^2(\alpha-\delta)]$$

Phase B,II:

$$F_x = -F_u(\sin^2\Phi_2 + 0.3\Phi_2 - 0.15\sin\Phi_2)$$

$$F_y = F_u(\Phi_2 - 0.5\sin 2\Phi_2 - 0.3\sin^2\Phi_2)$$

Phase C:

$$F_x = -F_u[\sin^2\Phi_2 - \sin^2(\alpha-\delta) + 0.15\sin 2(\alpha-\delta) - 0.15\sin 2\Phi_2 + 0.3(\Phi_2 - \alpha + \delta)]$$

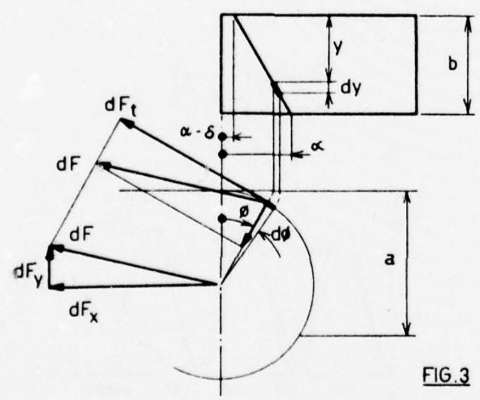


FIG.3

$$F_y = F_u[\Phi_2 - \alpha + \delta + 0.5\sin 2(\alpha-\delta) - 0.5\sin 2\Phi_2 + 0.3\sin^2(\alpha-\delta) - 0.3\sin^2\Phi_2] \quad (10)$$

In all these cases it is further

$$F = \sqrt{F_x^2 + F_y^2} \quad (11)$$

Expressions (10) and (11) apply to a single tooth. For several teeth cutting simultaneously it is

$$F = \sqrt{(\Sigma F_{xi})^2 + (\Sigma F_{yi})^2} \quad (12)$$

for i = 1 to z, where z is the number of the teeth.

Expressions (9),(10),(12) have been written into a computer program and evaluated and plotted for various combinations of depth of cut a, width of cut b, number of teeth z and particular values of β, K, s_t.

Examples of these various cases are given in Figs. 4 and 5. In all these cases the following parameters were used: $\beta = 30°$, $K = 2150 N/cm^2$, $s_t = 0.15 mm$, cutter diameter 2r = 6.35 mm. The depth of cut a and width of cut b are shown in the same scale for all the cases in corresponding sketches. The unfolded cuts are shown as well illustrating the phases A,B,C for one of the teeth. In Fig.4 case a) is Type II with z=2, with a very short phase B and corresponding

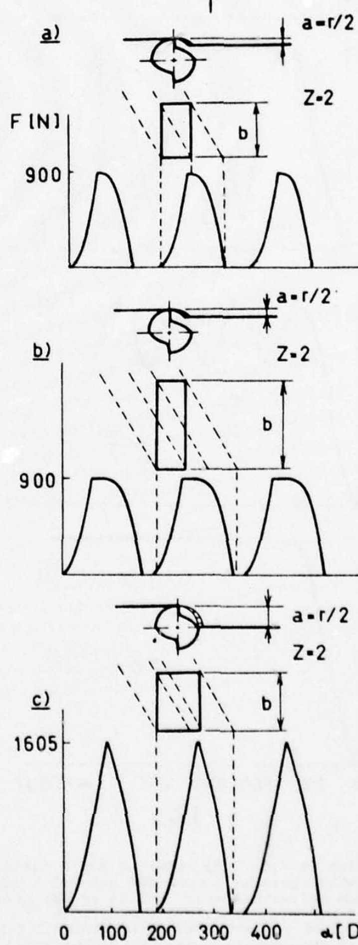


FIG.4

short flats at the tops of the force versus rotation curves. Case b) is the same but for width b which is larger; the force reaches the same maximum which stays longer constant during a larger phase B. The force cycle extends over a larger total engagement angle. Case c) differs from a) by double the depth of cut which makes it Type I. There are no flats on the tops

of the force curves and the maximum is higher. In Fig. 5, the case a) applies to z=1 and it corresponds to slotting, with $\Phi_2=180°$. It is a wide Type I case and the increase of force on one tooth is symmetrical to its decrease. This case gives the maximum force for a given value of b. Cases b),c),d) are the same as a) but with z=2,3,4 respectively. It may be seen how fast the force variation decreases with increasing overlap of teeth.

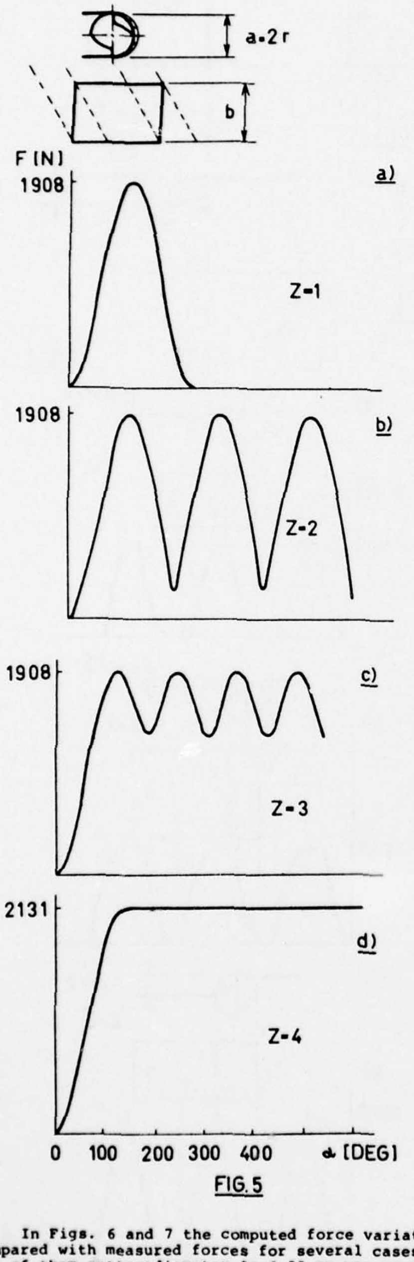


FIG.5

In Figs. 6 and 7 the computed force variation is compared with measured forces for several cases. In all of them cutter diameter 2r=6.35 mm was used and a value of K corresponding to $K=9.66 \times 10^5 s_t^{-0.17}$, K[N], s[mm]. Values of s_t: 6a) 0.038mm, b) 7a) 0.09mm, b) 0.02mm. Material of the workpiece was 1040 carbon steel with HB=166 kg//mm². The force scale is different in each case, however the geometric figures showing a and b *are drawn in the same scale. Graphs 6a) and b) are* Types I. Graph 7a) is Type II, graph b) is again Type I, however, with z=4 while all the three preceding ones have z=2. It may be seen that the computed and measured values are in good qualitative as well as quantitative agreement. The differences

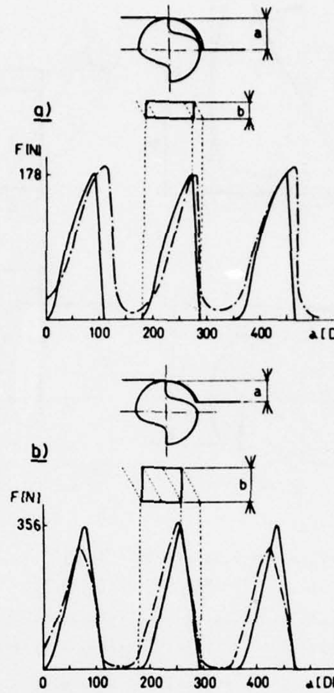


FIG.6

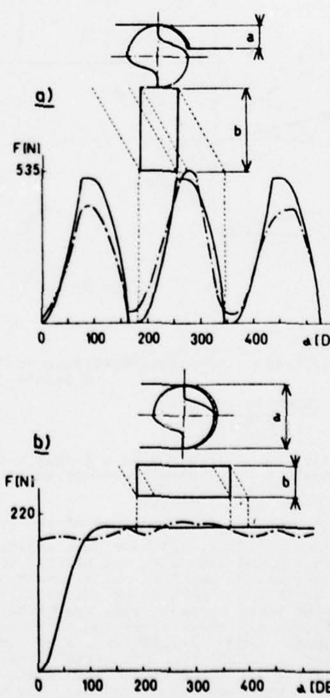


FIG.7

in 6b) and 7a) are due to the run-out of the cutter in the cutting tests.

THE TRANSIENTS

One of the most important transient cases is such where the cutter is approaching a plane side of a workpiece and is entering along a normal to it. Such an entrance is illustrated in three steps in Fig. 8 with the cutter moving upwards and above it the unfolded views of the cut surface. Cutting starts at $\phi=\Phi_1$ and ends at $\phi=\Phi_2$ for any point of the cutting edge, the whole cut being symmetrical with respect to axis X and extending to both sides of it by an angle ε. The depth of cut is denoted e. The formulae (6) for the cutting force apply again but the integration limits are different than in the preceding paragraph. Obviously, at the beginning, for small e, we have the Type II cycle with the force constant through phase 3. The limits for this case are:

$$\begin{aligned} &\text{for } \alpha\text{: A: } [\Phi_1, \Phi_2], \text{ B: } [\Phi_2, \Phi_1+\delta], \text{ C: } [\Phi_1+\delta, \Phi_2+\delta], \\ &\text{for } \Phi\text{: A: } [\Phi_1, \alpha], \text{ B: } [\Phi_1, \Phi_2], \text{ C: } [\alpha-\delta, \Phi_2]. \end{aligned} \qquad (13)$$

Then, as shown in case 2, when the depth of cut reaches the value e_m the phase B just shrinks to zero and the cutting edge reaches the maximum possible length b while it is in the central position. This represents, obviously, also the maximum magnitude of the cutting force. Further on, the cutting cycle becomes that of Type I and reaches its extreme for e=r as shown in case 3. In this case, again, the cutting force reaches the same maximum as in case 2. This applies strictly to one tooth only. However, cutting is extended over an engagement angle of 180°+ δ. This larger engagement angle means, of course, that forces established on individual teeth of a multitooth cutter start to overlap and this may lead to an increase of the maximum force depending on the

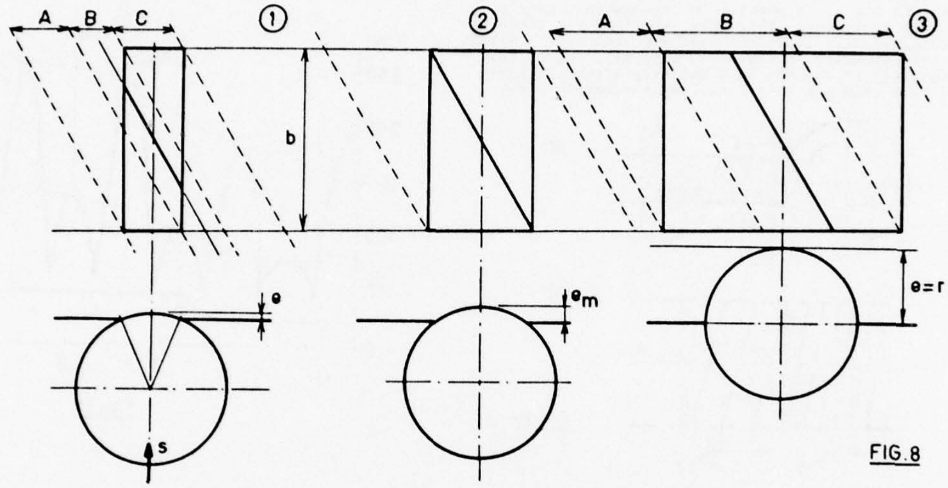


FIG.8

number of teeth. For a two-tooth cutter such an increase is small or none. This analysis is illustrated in Fig. 9. Cases a),b),c) have been derived by computation, case d) is given as actually measured. In all the three computed cases the same cutter radius r=3.175 mm and the same feed per tooth s_f=0.15 mm were employed, number of teeth z=2 for a) and c) and z=4 for b). There is a significant difference in the width of cut between cases a),b) where it is b=5 mm, resulting in a ratio of b/r=1.6 and case c) where it is b=21.6 mm resulting in a ratio of b/r=6.8. In the experiment the result of which is in d) the cutter radius was r=7.94 mm, z=2, s_f=0.13 mm, b=15mm. The horizontal coordinate in these graphs is the relative penetration of the cutter into the workpiece as expressed by the ratio e/r. It may be seen that in the first two cases the amplitudes of the periodic force reach very quickly the final maximum. In cases c) and d) the amplitude is increasing comparatively slowly. However, it reaches its maximum before the engagement of the cutter reaches its maximum of Φ_2= 180° at e/r=1. In the experimental case the run-out of the cutter causes periodic variation of the force amplitude once per revolution, i.e. once per every two teeth.

It is extremely important to understand the fast increase of the cutting force. For a two fluted cutter the maximum is reached at the depth of cut e_m which depends on the cutter radius r and width of cut b (for β=30°)

$$e_m = r\left(1-\cos\frac{b\tan\beta}{2r}\right) = r\left(1-\cos 0.289\,\frac{b}{r}\right) \qquad (14)$$

or approximately, $$e_m \approx \frac{b^2\tan^2\beta}{8r} = 0.0417\,\frac{b^2}{r} \qquad (15)$$

Thus, e.g.:

for $b = \frac{r}{2}$, $e_m = 0.01\ r$,

for $b = r$, $e_m = 0.04\ r$,

for $b = 2r$, $e_m = 0.17\ r$.

After this short distance of penetration the duration of the force increases but not its magnitude (for the 2 fluted cutter)and it is, of course, the magnitude which matters for breakage of the cutter. The short duration of the force still aggravates the matter because the transducer and, especially, the servo might not fully perceive the maximum of the force due to the filtering effect of their larger time constants.

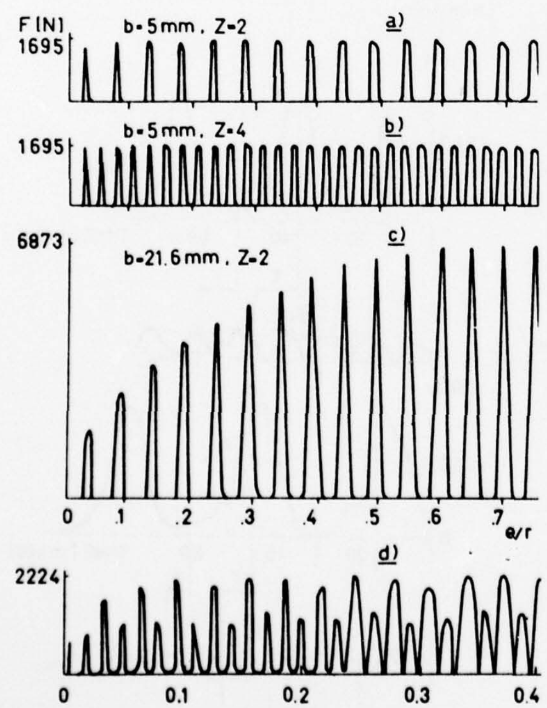


FIG.9

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THE TIME DELAY

Formulae (5) and (10) show that, with all other parameters constant, the force is proportional (or, at least approximately so) to the feed per tooth s_t which, itself is obtained as:

$$s_t = \frac{s}{n \times r}\,, \tag{16}$$

where s[mm/min]is the table velocity (feed rate), n/min is spindle speed and z is the number of teeth of the cutter. Thus, it would seem that the force is instantly proportional to table velocity s. However, it may be shown that there is a time delay included in this relationship. In Fig. 10a), first a simplified case is shown of milling a narrow surface (width A) with a single-tooth cutter. The individual cuts following the indicated position of the cutter are numbered 1, 2. . .,7. The distance of the first cuts is the chip thickness equal to the feed per tooth s_t. Imagine that at the moment when the tooth has just left cut 4, in position M, the table velocity s suddenly increases. Therefore, the feed per tooth s_t in cuts 5,6,7,.. is correspondingly greater. However, the corresponding increase in force will not be felt immediately in the moment M but only after the tooth will come into cut again, i.e. approximately after

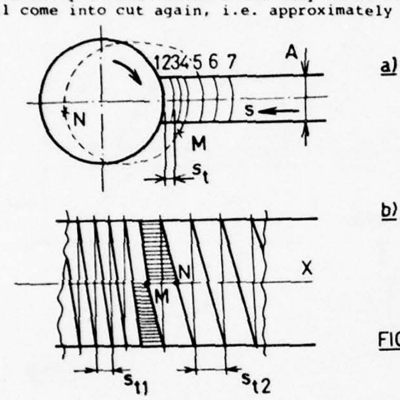

FIG.10

a full cutter revolution. If, instead, the table velocity s is suddenly increased when the tool is in point N, i.e. about half the revolution after cut 4, chip thickness in cut 5 will be increased by only half the final increase which will not apply until cut 6. In Fig. 10b) a simplified case is presented which illustrates what happens in the case of a two fluted cutter milling with full diameter (slotting), i.e. the dimension A of Fig. 10a) is now equal to cutter diameter. The simplification consists in neglecting the sinusoidal variation of the chip thickness which was described in Fig. 1 and assuming that every tooth moves along a straight line across the machined surface while it simultaneously moves with constant feed velocity. As soon as one tooth left the cut at the bottom the next tooth starts to cut at the top at the same X-position. At the beginning the feed per tooth is s_{t_1}. From point M on the feed velocity is doubled so that the new established feed per tooth $s_{t_2} = s_{t_1}$. From point M on the chip thickness (shown dashed) starts to increase until in Point N, one tooth period later, it reaches fully the new value s_{t_2}. Thus, it is obvious that a sudden increase in table velocity produces a corresponding change fully only after a delay of one to one and half tooth periods during which delay there may either be a gradual change or just vacant time depending on the ratio of the angle of engagement of the tooth to the tooth pitch.

In Fig. 11a) the result of an experiment is shown where the table velocity s was rather suddenly changed. The record of the force which is plotted above the record of table velocity is distorted because of a rather great run-out of the cutter in this experiment. Therefore two envelopes are drawn separately for the high and the low teeth. It is not possible to say exactly when the force reaches the new level but it is somewhere between τ_a=110 msec and τ_b=50 msec. The tooth period here was 60 msec as it corresponded to a 2 fluted cutter rotating at 500 rev/min = 8.33 rev/sec.

In Figs. 12a) and b) two records are shown where, artificially, instability was introduced in the servo of the milling machine so that the velocity of the table varied periodically. A record of only one radial component of the cutting force is shown as established on a rotating dynamometer. Therefore, it is sinusoidally modulated by the spindle speed n=8.33 rev/sec (period of 120 msec). The envelope of this record is indicated and it represents the magnitude of the force. The main period of the variation of table speed is between 250 and 320 msec. The delay between velocity and force variations is 40 to 50 msec while the tooth period is 30 msec.

All these records prove the point made in relation to Figs. 10a) and b). This delay is extremely significant for the stability of the adaptive control loop.

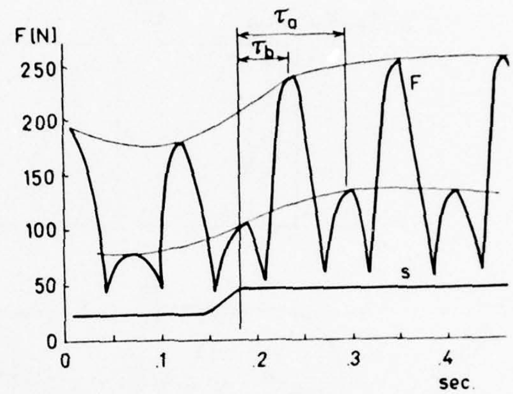

FIG.11

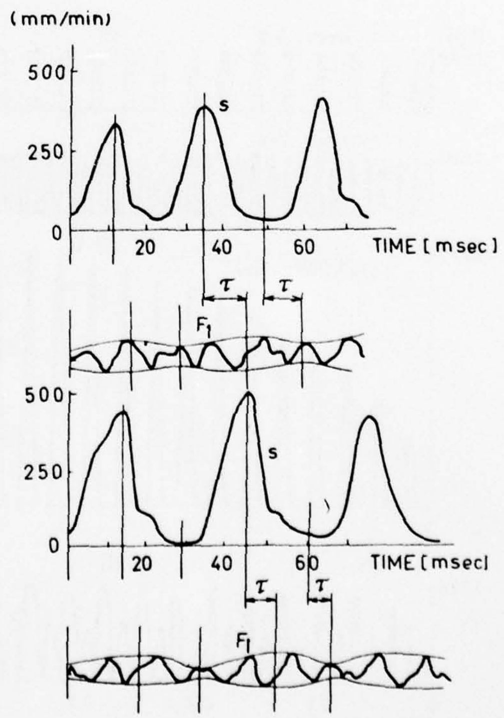

FIG. 12

References

1. R. Pickenbrink, Wachselkrafte und Schwingungen beim Frasvorgang, Ind. Anzeiger, 5.8.1955.
2. J. Tlusty, F. Koenigsberger, Specifications and Tests of Metal Cutting Machine Tools, UMIST Manchester, April 1970.

APPENDIX E

LISTING OF MICRO PROGRAM

```
      OVERLAY(FRANK,0,0)
      PROGRAM MICRO(INPUT,OUTPUT,FILE,BASE,TAPE,SUMMRY,TAPE2=INPUT,TAPE3
     1=OUTPUT,TAPE4=SUMMRY,TAPE5=BASE)
      COMMON /ANSR/IY,NO
      COMMON /TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3,
     1TP,TB,TS,IZ,D,G
      COMMON/MTOOL/MTCODE,MTDES(15),RTV,FMT(50),VMT(50),TI,TD,HPMAX,XM
     1,FMTMIN,FMTMAX,VMTMIN,VMTMAX
      COMMON/COST/XK0,XK1,XK2,CFEED,CTOOL,CDULL,CDEP,CPRE,CBATCH
     1,CEFEED,CMFEED,CRESH,CSET,CLOAD,CRTV
      COMMON/TIME/XM0,XM1,XM2
      COMMON/MTL/MTLCD,MTLGRP,MTLHRD,MTLCND,MTLNM(15)
      COMMON/MODEL/CONST,NOIN,INDEX(15),COEFF(15)
      COMMON/OPN/IOP,OPNAME(6),IDUM
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/MADA/F(20),V(20),T(20),ICF(20),NDP,NDP0,NDP1,NDP2,NDP3
     1,TLIMIT,VMIN,VMAX,FMIN,FMAX
      COMMON/MISC/ENDFIL,P,NL,PNAME(6),TLOAD,TC,NPMT
      COMMON/OUTPUT/HP,R,PPT
      DATA IY/1HY/,NO/1HN/
      CALL RETURN(6HSUMMRY)
      CALL RETURN(4HBASE)
      WRITE(3,100)
  100 FORMAT(//T20,*MICRO COST ESTIMATION SYSTEM*/T20,*DEVELOPED BY*,
     1* METCUT RESEARCH ASSOC. INC.*)
C
C  INPUT DATA BASE INITIALS
C
      WRITE(3,110)
  110 FORMAT(/* INPUT DATA BASE INITIALS*/* =*)
      READ(2,115)NBASE
  115 FORMAT(A3)
      WRITE(5,120)NBASE,NBASE
  120 FORMAT(1H.,A3,2HA.,1H.,A3,2HB.)
      REWIND 5
      READ(5,125)NBASEA,NBASEB
  125 FORMAT(2A6)
C
C  INPUT PART NAME
C
  127 WRITE(3,130)
  130 FORMAT(/* INPUT PART NAME (MAX 24 CHAR)*/* =*)
      READ(2,135)(PNAME(I),I=1,6)
  135 FORMAT(6A4)
      WRITE(3,542)
  542 FORMAT(/* INPUT NO. PARTS MACHINED AT ONE TIME ON M/T*/* =*)
      READ(2,*)NPMT
C
C  INPUT WORKPIECE MATERIAL CODE
C
  137 WRITE(3,140)
  140 FORMAT(/* INPUT WORKPIECE MATL CODE (0=LISTING)*/* =*)
      READ(2,*)MTLCD
```

```
C
C  CALL MTLIST
C
      IF(MTLCD.EQ.0)CALL OVERLAY(5HFRANK,1,0)
      IF(MTLCD.EQ.0)GO TO 137
C
C  CALL MTCHK
C
      CALL OVERLAY(5HFRANK,2,0)
      IF(ENDFIL.EQ.-1.)GO TO 137
      IF(ENDFIL.EQ.0.)GO TO 180
  143 WRITE(3,145)MTLCD,NBASEA
  145 FORMAT(/* MATERIAL CODE*,1X,I5,1X,*IS NOT IN DATA BASE*,1X,A10/
     1* NEW MATERIAL  *)
      READ(2,150)IANS
  150 FORMAT(A1)
      IF(IANS.EQ.IY)GO TO 137
      IF(IANS.EQ.NO)GO TO 230
      WRITE(3,155)
  155 FORMAT(/* YES OR NO ONLY. TRY AGAIN*)
      GO TO 143
C
C  INPUT OPERATION CODE
C
  180 WRITE(3,185)
  185 FORMAT(/* INPUT OPERATION CODE (0=LIST)*/* =*)
      READ(2,*)IOP
C
C  CALL OPLIST
C
      IF(IOP.EQ.0)CALL OVERLAY(5HFRANK,3,0)
      IF(IOP.EQ.0)GO TO 180
C
C  CALL OPCHK
C
      CALL OVERLAY(5HFRANK,4,0)
      IF(ENDFIL.EQ.-1.)GO TO 180
      IF(ENDFIL.EQ.0)GO TO 196
  205 WRITE(3,200)IOP
  200 FORMAT(/* OPERATION CODE*,1X,I3,1X,*DOES NOT EXIST*/
     1* NEW OPERATION!  *)
      READ(2,1000)IANS
      IF(IANS.EQ.IY)GO TO 180
      IF(IANS.EQ.NO)GO TO 215
      WRITE(3,155)
      GO TO 205
C
C  INPUT TOOL CODE
C
196   WRITE(3,197)
197   FORMAT(/* INPUT TOOL CODE (0=LIST)*/* =*)
      READ(2,*)ITLCD
C
C  CALL TLIST
```

```
C
      IF(ITLCD.EQ.0)CALL OVERLAY(5HFRANK,5,0)
      IF(ITLCD.EQ.0)GO TO 196
C
C  CALL MTS
C
      CALL OVERLAY(5HFRANK,6,0)
      IF(ENDFIL.EQ.-1.)GO TO 196
      IF(ENDFIL.EQ.0)GO TO 450
199   WRITE(3,198)ITLCD
198   FORMAT(/* CODE *,I5,* DOES NOT EXIT.  NEW TOOL!*/* =*)
      READ(2,1000)IANS
      IF(IANS.EQ.IY)GO TO 196
      IF(IANS.EQ.NO)GO TO 215
      WRITE(3,155)
      GO TO 199
C
C  INPUT MACHINE TOOL CODE
C
450   WRITE(3,451)
451   FORMAT(/* INPUT M/T CODE (0=LIST)*/* =*)
      READ(2,*)MTCODE
C
C  CALL WCLIST
C
      IF(MTCODE.EQ.0)CALL OVERLAY(5HFRANK,7,0)
      IF(MTCODE.EQ.0)GO TO 450
C
C  CALL MMS
C
      CALL OVERLAY(5HFRANK,8,0)
      IF(ENDFIL.EQ.-1.)GO TO 450
      IF(ENDFIL.EQ.0)GO TO 195
460   WRITE(3,461)MTCODE
461   FORMAT(/* CODE *,I5,* DOES NOT EXIT.  NEW M/T CODE!*/* =*)
      READ(2,1000)IANS
      IF(IANS.EQ.IY)GO TO 450
      IF(IANS.EQ.NO) GO TO 215
      WRITE(3,155)
      GO TO 460
195   WRITE(3,217)
217   FORMAT(/* INPUT:*,T10,*SETUP TIME (MIN),*/T10,*LOAD-UNLOAD TIME*
     1* (MIN),*/T10,*LOT SIZE*/* =*)
      READ(2,*)TO,TLOAD,NL
C
C  CALL OPER
C
850   CALL OVERLAY(5HFRANK,9,0)
      IF(IDUM.EQ.-1)GO TO 215
      GO TO (201,202,203,204)IDUM
C
C  CALL FEMCUT
C
201   CALL OVERLAY(5HFRANK,19,0)
```

```
C
C   READ DATA FOR ALL THREE LEVELS OF MACHINABILITY DATA
C
        NDP=0
        NDP0=0
        NDP1=0
        NDP2=0
        NDP3=0
        DO 830 I=1,3
        GO TO (800,810,820)I
C
C   CALL PEMDA1
C
800     CALL OVER        GO TO 830
C
C   CALL PEMDA2
C
810     CALL OVERLAY(5HFRANK,11,0)
        GO TO 830
C
C   CALL PEMDA3
C
820     CALL OVERLAY(5HFRANK,12,0)
        IF(NDP3.EQ.0)GO TO 830
C
C   INPUT MAX TOOL LIFE FOR MODEL
C
        WRITE(3,8201)
8201    FORMAT(/* INPUT MAX TOOL LIFE (0=NO LIMIT)*/* =*)
        READ(2,*)TLIMIT
821     WRITE(3,822)
822     FORMAT(/* CONTOUR PLOT!  *)
        READ(2,1000)IANS
        IF(IANS.EQ.IY)GO TO 823
        IF(IANS.EQ.NO)GO TO 830
        WRITE(3,155)
        GO TO 821
C
C   CALL CONTOUR
823     CALL OVERLAY(5HFRANK,13,0)
830     CONTINUE
        IF(NDP.NE.0)CALL OVERLAY(5HFRANK,14,0)
        IF(NDP.EQ.0)WRITE(3,840)
840     FORMAT(/* NO DATA POINTS WERE FOUND IN MACHINABILITY FILES*)
C
C   CALL PEMCNL
C
500     CALL OVERLAY(5HFRANK,15,0)
C
C   CALL PEMPRT
C
        IF(NDP0.NE.0)CALL OVERLAY(5HFRANK,14,0)
        IF(NDP0.NE.0)GO TO 500
        GO TO 210
```

```
202    CALL OVERLAY(5HFRANK,16,0)
       GO TO 210
203    CALL OVERLAY(5HFRANK,17,0)
       GO TO 210
204    CALL OVERLAY(5HFRANK,18,0)
210    CONTINUE
215    WRITE(3,220)
220    FORMAT(/* NEW TOOL(1)*/* NEW OPERATION(2)*/* NEW PART(3)*/
      1* STOP(4)*/* =*)
       READ(2,*)IGO
       GO TO (196,180,127,230)IGO
230    WRITE(3,240)
240    FORMAT(/* SUMMARY OF OUTPUT IS IN FILE NAMED SUMMRY*/
      1* GOOD LUCK""*//)
1000   FORMAT(A1)
       REWIND 4
       CALL EXIT
       END
       SUBROUTINE PEMEGN(FF,VV,TT,C,TM)
C
C  THIS PROGRAM CALULATES COSTS AND TIMES FOR PERIPHERAL END MILLING
C
       COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3,
      1TP,TB,TS,IZ,D,G
       COMMON/MTOOL/MTCODE,MTDES(15),RTV,FMT(50),VMT(50),TI,TD,HPMAX,XM,
      1FMTMIN,FMTMAX,VMTMIN,VMTMAX
       COMMON/COST/XK0,XK1,XK2,CFEED,CTOOL,CDULL,CDEP,CFRE,CBATCH
      1,CRFEED,CMFEED,CRESH,CSET,CLOAD,CRTV
       COMMON/TIME/XM0,XM1,XM2
       COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
       COMMON/MISC/ENDFIL,P,NL,PNAME(6),TLOAD,TO
       COMMON/OUTPUT/HP,R,PPT
       IF(CP.EQ.0)K1=1
       IF(TB.EQ.0)K2=1
       IF(CC.EQ.0)K3=1
C
C  CALCULATE M0,M1,M2,K0,K1,K2
C
       TRTV=RDIST/RTV
       TSET=TO/FLOAT(NL)
       XM0=TRTV+TLOAD+TSET
       XM1=(E+XL)*RDACT*ADACT
       XM2=XL*RDACT*ADACT*TD
C
C
C
       CRTV=XM*TRTV
       CLOAD=XM*TLOAD
       CSET=XM*TSET
       XK0=XM*XM0
       XK1=XM*XM1
C
C  COMPUTE TOOL COSTS
C
```

```
      DULL=XM*XM2
      DEF=CF/FLOAT(K1+1)
      RESH=G*TS
      WHEEL=CW
      PRE=G*TP
C
C
      VOLA=E*RDACT*ADACT
      VOL=XL*ADACT*RDACT
      XK2=XM*XM2+VOL*(DEP+RESH+WHEEL+PRE)
      R=12.*FF*VV*FLOAT(I2)*RDACT*ADACT/3.14159/D
      CFEED=XK1/R
      CDULL=DULL/R/TT
      CDEP=VOL*DEP/R/TT
      CRESH=VOL*(RESH+WHEEL)/R/TT
      CPRE=VOL*PRE/R/TT
      CTOOL=XK2/R/TT
      CEFEED=XM*VOLA/R
      CMFEED=XM*VOL/R
C
C  CALCULATE TIME, COST, HP, PCNT TOOL USED
C
      C=XKC+XK1/R+XK2/R/TT
      TM=XMC+XM1/R+XM2/R/TT
      HP=R*P
      CBATCH=C*FLOAT(NL)
      PPT=R*TT/VOL
      RETURN
      END
      FUNCTION XTL(V,F)
      DIMENSION VAR(20)
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      COMMON/MODEL/CONST,NOIN,INDEX(15),COEFF(15)
      COMMON/MADA/FF(20),VV(20),TT(20),ICF(20),NDP,NDPC,NDP1,NDP2,NDP3
     1,TLIMIT,VMIN,VMAX,FMIN,FMAX
      VAR(1)=ALOG(V)
      VAR(2)=ALOG(F)
      VAR(3)=ALOG(RDACT)
      VAR(4)=ALOG(ADACT)
      VAR(5)=VAR(1)*VAR(1)
      VAR(6)=VAR(2)*VAR(2)
      VAR(7)=VAR(3)*VAR(3)
      VAR(8)=VAR(4)*VAR(4)
      VAR(9)=VAR(1)*VAR(2)
      VAR(10)=VAR(1)*VAR(3)
      VAR(11)=VAR(1)*VAR(4)
      VAR(12)=VAR(2)*VAR(3)
      VAR(13)=VAR(2)*VAR(4)
      VAR(14)=VAR(3)*VAR(4)
      XTL=CONST
      DO 100 I=1,NOIN
      KK=INDEX(I)
100   XTL=XTL+COEFF(I)*VAR(KK)
      XTL=EXP(XTL)
```

```
      IF(TLIMIT.EQ.0)RETURN
      IF(XTL.GT.TLIMIT)XTL=TLIMIT
      RETURN
      END
      OVERLAY(FRANK,1,0)
      PROGRAM MTLIST
C
C  THIS PROGRAM LISTS MATERIAL FILE FOR MICRO SYSTEM
C
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/MTL/MTLCD,MTLGRP,MTLHRD,MTLCND,MTLNM(15)
      WRITE(3,80)
   80 FORMAT(/* CODE*,10X,*DESCRIPTION*/)
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,2)
90    READ(5,100)ICHK,ICHK1,ICHK2,ICHK3,(MTLNM(I),I=1,15)
100   FORMAT(I5,1X,2(I3,1X),I2,1X,15A4)
      IF(EOF(5).NE.0)GO TO 120
      WRITE(3,110)ICHK,(MTLNM(I),I=1,15)
  110 FORMAT(1X,I5,1X,15A4)
      GO TO 90
  120 CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY(FRANK,2,0)
      PROGRAM MTCHK
C
C  THIS PROGRAMS CHECKS AND CONFIRMS MATERIAL CODE FOR MICRO SYSTEM
C
      COMMON /ANSR/IY,NO
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/MTL/MTLCD,MTLGRP,MTLHRD,MTLCND,MTLNM(15)
      COMMON/MISC/ENDFIL
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,2)
100   READ(5,110)ICHK,MTLGRP,MTLHRD,MTLCND,(MTLNM(I),I=1,15)
110   FORMAT(I5,1X,2(I3,1X),I2,1X,15A4)
      IF(EOF(5).NE.0)GO TO 150
      IF(ICHK.NE.MTLCD)GO TO 100
  115 WRITE(3,120)MTLCD,(MTLNM(I),I=1,13)
  120 FORMAT(/* CODE*,1X,I5,1X,*IS*,1X,13A4/* CORRECT!  *)
      READ(2,130)IANS
  130 FORMAT(A1)
      IF(IANS.EQ.NO)ENDFIL=-1.
      IF(IANS.EQ.NO)GO TO 160
      IF(IANS.EQ.IY)GO TO 150
      WRITE(3,135)
  135 FORMAT(/* YES OR NO ONLY. TRY AGAIN*)
      GO TO 115
  150 ENDFIL=EOF(5)
  160 CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY(FRANK,3,0)
```

```
      PROGRAM OPLIST
C
C   THIS PROGRAM LISTS OPERATION FILE FOR MICRO SYSTEM
C
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/OPN/IOP,OPNAME(6),IDUM
      WRITE(3,50)
   50 FORMAT(/* OP CODE*,10X,*DESCRIPTION*/)
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,6)
   60 READ(5,70)ICHK,(OPNAME(I),I=1,6)
   70 FORMAT(I3,1X,6A4)
      IF(EOF(5).NE.0)GO TO 120
      WRITE(3,80)ICHK,(OPNAME(I),I=1,6)
   80 FORMAT(3X,I3,4X,6A4)
      GO TO 60
  120 CALL RETURN(4HBASE)
      END
      OVERLAY(FRANK,4,0)
      PROGRAM OPCHK
C
C   THIS PROGRAM CHECKS AND VERIFIES OPERATION CODE FOR MICRO SYSTEM
C
      COMMON/OPN/IOP,OPNAME(6),IDUM
      COMMON /ANSR/IY,NO
      COMMON/MISC/ENDFIL
      COMMON/DBASE/NBASEA,NBASEB
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,6)
  100 READ(5,110)ICHK,(OPNAME(I),I=1,6)
  110 FORMAT(I3,1X,6A4)
      IF(EOF(5).NE.0)GO TO 150
      IF(ICHK.NE.IOP)GO TO 100
  115 WRITE(3,120)IOP,(OPNAME(I),I=1,6)
  120 FORMAT(* CODE*,1X,I3,1X, *IS*,1X,6A4/* CORRECT!  *)
      READ(2,130)IANS
  130 FORMAT(A1)
      IF(IANS.EQ.NO)ENDFIL=-1.
      IF(IANS.EQ.NO)GO TO 160
      IF(IANS.EQ.IY) GO TO 150
      WRITE(3,135)
  135 FORMAT(/* YES OR NO ONLY. TRY AGAIN*)
      GO TO 115
  150 ENDFIL=EOF(5)
  160 CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY (FRANK,5,0)
      PROGRAM TLIST
C
C   THIS PROGRAM LISTS TOOLS IN TOOL FILE
C
      COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3,
     1TP,TB,TS,IZ,D,G
```

```
      COMMON/DBASE/NBASEA,NBASEB
      WRITE(3,50)
50    FORMAT(/* TOOL CODE*,10X,*DESCRIPTION*/)
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,4)
60    READ(5,70)ICHK,ICHK1,ICHK2,(TLDES(I),I=1,15)
70    FORMAT(I5,1X,I3,1X,I1,1X,15A4)
      IF(EOF(5).NE.0)GO TO 120
      WRITE(3,80)ICHK,(TLDES(I),I=1,15)
80    FORMAT(1X,I5,4X,15A4)
      READ(5,81)XCHK
81    FORMAT(F6.0)
      GO TO 60
120   CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY(FRANK,6,0)
      PROGRAM MTS
C
C  THIS PROGRAM CHECKS AND OBTAINS TOOL INFO FOR MICRO SYSTEM
C
      COMMON /ANSR/IY,NO
      COMMON /TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3,
     1TP,TB,TS,IZ,D,G
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/MISC/ENDFIL,P
C
C  CHECK TOOL FILE FOR TOOL DATA
C
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,4)
   70 READ(5,80)ICHK,ITGRP,ITTYPE,(TLDES(J),J=1,15)
      IF(EOF(5).NE.0)GO TO 150
   80 FORMAT(I5,1X,I3,1X,I1,1X,15A4)
      READ(5,85)CP,CC,CW,K1,K2,K3,TP,TB,TS,IZ,D,G
85    FORMAT(F6.2,1X,F6.2,1X,F5.2,1X,I3,1X,I3,1X,I3,1X,F5.2,1X,F5.2,1X,
     1F5.2,1X,I2,1X,F6.3,1X,F5.2)
      G=G/60.
      IF(ICHK.NE.ITLCD)GO TO 70
90    WRITE(3,100)ICHK,(TLDES(J),J=1,13)
100   FORMAT(/* CODE *,I5,* IS *,13A4/* CORRECT!  *)
      READ(2,110)IANS
  110 FORMAT(A1)
      IF(IANS.EQ.NO)ENDFIL=-1.
      IF(IANS.EQ.NO)GO TO 150
      IF(IANS.EQ.IY)GO TO 140
      WRITE(3,115)
  115 FORMAT(/* YES OR NO ONLY. TRY AGAIN*/)
      GO TO 90
140   WRITE(3,145)
  145 FORMAT(/* INPUT UNIT HP*/* =*)
      READ(2,*)P
      ENDFIL=EOF(5)
150   CALL RETURN(4HBASE)
```

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MATHEMATICAL MODELING OF MATERIAL REMOVAL PROCESSES FOR IMPROVE--ETC(U)
SEP 77 V A TIPNIS, S A VOGEL, S C BUESCHER F33615-76-C-5254
UNCLASSIFIED 1566-23599 AFML-TR-77-154 NL

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END
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```
      RETURN
      END
      OVERLAY(FRANK,7,0)
      PROGRAM WCLIST
C
C  THIS PROGRAM LISTS M/T IN M/T FILE
C
      COMMON/MTOOL/MTCODE,MTDES(15),RTV,FMT(50),VMT(50),TI,TD,HPMAX,XM,
     1FMTMIN,FMTMAX,VMTMIN,VMTMAX
      COMMON/DBASE/NBASEA,NBASEB
      WRITE(3,50)
50    FORMAT(/* M/T CODE*,10X,*DESCRIPTION*/)
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,3)
60    READ(5,70)ICHK,MTTYPE,(MTDES(I),I=1,15)
70    FORMAT(I5,1X,I2,1X,15A4)
      IF(EOF(5).NE.0)GO TO 160
      WRITE(3,80)ICHK,(MTDES(I),I=1,15)
80    FORMAT(1X,I5,4X,15A4)
      READ(5,90)XCHK,XCHK1,XCHK2,XCHK3,N
      NM2=N-2
90    FORMAT(F6.0,1X,3(F5.0,1X),I3)
      N2=N/2
100   MTTYPE=MTTYPE-10
      IF(MTTYPE.GE.10)GO TO 100
      GO TO (110,110,130,140)MTTYPE
110   READ(5,150)(FMT(I),VMT(I),I=1,N2)
      GO TO 60
130   READ(5,150)(VMT(I),I=1,2),(FMT(I),I=1,NM2)
      GO TO 60
140   READ(5,150)(FMT(I),I=1,2),(VMT(I),I=1,NM2)
150   FORMAT(8(F6.3,1X))
      GO TO 60
160   CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY(FRANK,10,0)
      PROGRAM MMS
C
C  THIS PROGRAM CHECKS M/T CODE AND OBTAINS M/T INFO
C
      COMMON/MISC/ENDFIL,F,NL,FNAME(6),TLOAD,TO,NPMT
      COMMON/ANSR/IY,NO
      COMMON/MTOOL/MTCODE,MTDES(15),RTV,FMT(50),VMT(50),TI,TD,HPMAX,XM,
     1FMTMIN,FMTMAX,VMTMIN,VMTMAX
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3,
     1TP,TB,TS,IZ,D,G
C
C  CHECK,M/T FILE FOR DATA
C
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEA,2HCY,3)
70    READ(5,80)ICHK,MTTYPE,(MTDES(I),I=1,15)
```

```
80    FORMAT(I5,1X,I2,1X,15A4)
      IF(EOF(5).NE.0)GO TO 150
      READ(5,85)RTV,TI,TD,HPMAX,N,XM
85    FORMAT(F6.2,1X,3(F5.2,1X),I3,1X,F6.0)
      XM=XM/60./FLOAT(NFMT)
      NM2=N-2
      N2=N/2
C
C  READ M/T LIMITS ACCORDING TO TYPE TOOL
C
86    MTTYPE=MTTYPE-10
      IF(MTTYPE.GE.10)GO TO 86
      GO TO (91,91,93,94)MTTYPE
91    READ(5,95)(FMT(I),VMT(I),I=1,N2)
      FMTMIN=FMT(1)
      FMTMAX=FMT(N2)
      VMTMIN=VMT(1)
      VMTMAX=VMT(N2)
      GO TO 96
93    READ(5,95)(VMT(I),I=1,2),(FMT(I),I=1,NM2)
      FMTMIN=FMT(1)
      FMTMAX=FMT(NM2)
      VMTMIN=VMT(1)
      VMTMAX=VMT(2)
      GO TO 96
94    READ(5,95)(FMT(I),I=1,2),(VMT(I),I=1,NM2)
      FMTMIN=FMT(1)
      FMTMAX=FMT(2)
      VMTMIN=VMT(1)
      VMTMAX=VMT(NM2)
95    FORMAT(8(F6.3,1X))
96    CONTINUE
C
C  CONVERT M/T LIMITS TO IPT AND FPM
C
      FMTMIN=FMTMIN/FLOAT(IZ)/VMTMAX
      FMTMAX=FMTMAX/FLOAT(IZ)/VMTMIN
      VMTMIN=VMTMIN*.262*D
      VMTMAX=VMTMAX*.262*D
      IF(ICHK.NE.MTCODE)GO TO 70
99    WRITE(3,100)ICHK,(MTDES(I),I=1,13)
100   FORMAT(/* CODE *,I5,* IS *,13A4/* CORRECT!  *)
      READ(2,110)IANS
110   FORMAT(A1)
      IF(IANS.EQ.NO)ENDFIL=-1.
      IF(IANS.EQ.NO)GO TO 150
      IF(IANS.EQ.IY)GO TO 140
      WRITE(3,115)
115   FORMAT(/* YES OR NO ONLY. TRY AGAIN*/)
      GO TO 99
140   ENDFIL=EOF(5)
150   CALL RETURN(4HBASE)
      RETURN
      END
```

```
      OVERLAY(FRANK,11,0)
      PROGRAM OPER
C
C  THIS PROGRAM CHOOSES OPERATION SUBROUTINES FOR MICRO SYSTEM
C
      COMMON/OPN/IOP,OPNAME(6),IDUM
      IF(IOP.EQ.72)GO TO 50
      IF(IOP.EQ.56)GO TO 60
      IF(IOP.EQ.900)GO TO 70
      IF(IOP.EQ.71)GO TO 80
      WRITE(3,40)IOP
   40 FORMAT(/* OPERATION *,I3,* DOES NOT EXIST*/)
      IDUM=-1
      RETURN
50    IDUM=1
      RETURN
60    IDUM=2
      RETURN
70    IDUM=3
      RETURN
80    IDUM=4
      RETURN
      END
      OVERLAY(FRANK,12,0)
      PROGRAM PEMDA1
C
C  THIS PROGRAM SEARCHES FOR LEVEL 1 MACHINABILITY DATA AND
C  RETURNS DATA FOR OUTPUT IN PEMPRT
C
      DIMENSION ICODE(12),MCODE(12)
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      COMMON/MTL/MTLCD,MTLGRP,MTLHRD,MTLCND,MTLNM(15)
      COMMON/OPN/IOP,OPNAME(6),IDUM
      COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CF,CC,CW,K1,K2,K3,
     1TP,TB,TS,IZ,D,G
      COMMON/MADA/F(20),V(20),T(20),ICF(20),NDP,NDP0,NDP1,NDP2,NDP3
C
C  READ DATA FROM MADA1 FILE
C
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEB,2HCY,1)
100   READ(5,110)(ICODE(I),I=1,12)
110   FORMAT(12(I3,1X))
      IF(EOF(5).NE.0)GO TO 210
      READ(5,110)(MCODE(I),I=1,12)
      READ(5,120)MINHRD,MAXHRD,ICND,DC,NTM
120   FORMAT(I3,1X,I3,1X,I2,1X,F6.3,1X,I2)
      VV=0
      DO 130 I=1,NTM
      READ(5,140)ITMAT,XCHK1,XCHK2,XCHK3,XCHK4,XCHK5
      IF(ITMAT.NE.ITGRP)GO TO 130
      VV=XCHK1
      F1=XCHK2
```

```
      F2=XCHK3
      F3=XCHK4
      F4=XCHK5
130   CONTINUE
140   FORMAT(I3,1X,F4.0,1X,4(F5.3,1X))
      IF(VV.EQ.0)GO TO 100
C
C  CHECK ALL VARIABLES FOR VALIDITY OF DATA
C
      DO 150 I=1,12
150   IF(IOP.EQ.ICODE(I))GO TO 160
      GO TO 100
160   DO 170 I=1,12
170   IF(MTLGRP.EQ.MCODE(I))GO TO 180
      GO TO 100
180   IF(MTLHRD.LT.MINHRD)GO TO 100
      IF(MTLHRD.GT.MAXHRD)GO TO 100
      IF(MTLCND.NE.ICND)GO TO 100
C
C  CHECK FOR TYPE CUT BY DEPTH OF CUT. ALLOW +OR-.50 BAND WIDTH
C
      IF(RDACT.LT..5*DC)GO TO 100
      IF(RDACT.GT.1.5*DC)GO TO 100
C
C  DATA NOT VALID FOR DIAMETER GREATER THAN 3'
C
      IF(D.GT.3.)GO TO 100
C
C  DATA IS VALID.  CHOOSE CORRECT FEED DEPENDING ON DIA. OF END MILL
C
      NDP1=3
      IF(D.LT..375)FF=F1
      IF(D.GE..375.AND.D.LT..625)FF=F2
      IF(D.GE..625.AND.D.LT..875)FF=F3
      IF(D.GE..875)FF=F4
C
C  ADJUST SPEED BY DEPTH OF CUT: SPEED=(D1/D2)*V1+V1)/2
C  WHERE: D1=HANDBOOK DEPTH OF CUT, D2=ACTUAL DEPTH OF CUT,
C         V1=HANDBOOK SPEED, SPEED=ACTUAL SPEED
C
      VV=(DC/RDACT*VV+VV)/2.
C
C  SET UP F,V,T,ICF ARRAY FOR 30,60,90 MINUTES TOOL LIFE
C
      DO 200 I=1,3
      J=I+NDP
      V(J)=VV
      F(J)=FF
      T(J)=I*30
      ICF(J)=0
200   CONTINUE
C
C  ADD 3 TO NO. DATA POINTS
C
```

```
      NDP=NDP+3
210   CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY(FRANK,13,0)
      PROGRAM PEMDA2
C
C  THIS PROGRAM SEARCHES FOR LEVEL 2 MACHINABILITY DATA FOR
C  OUTPUT IN PEMPPT
C
      DIMENSION ICHK(5)
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      COMMON/MTL/MTLCD,MTLGRP,MTLHRD,MTLCND,MTLNM(15)
      COMMON/OPN/IOP,OPNAME(6),IDUM
      COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CF,CC,CW,K1,K2,K3,
     1TP,TB,TS,IZ,D,G
      COMMON/MADA/F(20),V(20),T(20),ICF(20),NDP,NDP0,NDP1,NDP2,NDP3
      CMIN=99.E20
      TMIN=99.E20
      NPTS=0
C
C  READ DATA FROM MADA2 FILE
C
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEB,2HCY,2)
100   READ(5,110)(ICHK(I),I=1,4),N
      IF(EOF(5).NE.0)GO TO 150
110   FORMAT(I3,1X,I5,1X,I5,1X,I3,1X,I3)
      DO 140 I=1,N
C
      READ(5,120)XCHK1,XCHK2,FF,VV,TT
120   FORMAT(2(F5.3,1X),3(F6.3,1X))
C
C  CHECK ALL VARIABLES FOR VALIDITY OF DATA. ALLOW +OR-.50 BAND ON RD
C
      IF(IOP.NE.ICHK(1))GO TO 140
      IF(MTLCD.NE.ICHK(2))GO TO 140
      IF(ITLCD.NE.ICHK(3))GO TO 140
      IF(RDACT.LT..5*XCHK1.OR.RDACT.GT.1.5*XCHK1)GO TO 140
      IF(ADACT.LT..5*XCHK2.OR.ADACT.GT.1.5*XCHK2)GO TO 140
C
C  DATA IS VALID.  CHECK FOR MIN COST AND MIN TIME
C
      NPTS=NPTS+1
      CALL PEMEQN(FF,VV,TT,COST,TIME)
      IF(COST.GT.CMIN)GO TO 130
      CMIN=COST
      VMINC=VV
      FMINC=FF
      TMINC=TT
      ICFC=ICHK(4)
130   IF(TIME.GT.TMIN)GO TO 140
      TMIN=TIME
```

```
      VMINT=VV
      FMINT=FF
      TMINT=TT
      ICFT=ICHK(4)
140   CONTINUE
      GO TO 100
C
C  SET UP F,V,T,ICF,ARRAY FOR MIN COST AND MIN TIME
C
150   IF(NPTS.EQ.0)GO TO 160
      F(NDP+1)=FMINC
      V(NDP+1)=VMINC
      T(NDP+1)=TMINC
      ICF(NDP+1)=ICFC
      F(NDP+2)=FMINT
      V(NDP+2)=VMINT
      T(NDP+2)=TMINT
      ICF(NDP+2)=ICFT
      NDP2=2
      NDP=NDP+2
160   CONTINUE
      CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY(FRANK,14,0)
      PROGRAM PEMDA3
C
C  THIS PROGRAM SEACRCHES FOR LEVEL 3 MACHINABILITY DATA
C  FOR OUTPUT IN PEMPRT
C
      DIMENSION ICHK(5)
      EXTERNAL XTL
      COMMON/DBASE/NBASEA,NBASEB
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      COMMON/MTL/MTLCD,MTLGRP,MTLHRD,MTLCND,MTLNM(15)
      COMMON/OPN/IOP,OPNAME(6),IDUM
      COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3
     1,TF,TE,TS,IZ,D,G
      COMMON/MADA/F(20),V(20),T(20),ICF(20),NDP,NDP0,NDP1,NDP2,NDP3
     1,TLIMIT,VMIN,VMAX,FMIN,FMAX
      COMMON/MODEL/CONST,NOIN,INDEX(15),COEFF(15)
      COMMON/MTOOL/MTCODE,MTDES(15),RTV,FMT(50),VMT(50),TI,TD,HPMAX,XM,
     1FMTMIN,FMTMAX,VMTMIN,VMTMAX
      CMIN=99.E20
      TMIN=99.E20
      NPTS=0
C
C  READ DATA FROM MADA3 FILE
C
      CALL RETURN(4HBASE)
      CALL PERMFIL(ERR,6HATTACH,4HBASE,NBASEB,2HCY,3)
100   READ(5,110)(ICHK(I),I=1,5)
110   FORMAT(I3,1X,I5,1X,I5,1X,I3,1X,I4)
      IF(EOF(5).NE.0)GO TO 200
```

```
      READ(5,120)RDMIN,RDMAX,ADMIN,ADMAX
120   FORMAT(4(F5.3,1X))
      READ(5,130)FMIN,FMAX,VMIN,VMAX,TLMIN,TLMAX
130   FORMAT(6(F6.3,1X))
      READ(5,140)CONST,NOIN
140   FORMAT(E15.3,1X,I2)
      READ(5,150)(INDEX(I),I=1,NOIN)
150   FORMAT(20(I2,1X))
      NLINES=NOIN/4
      NREM=NOIN-NLINES*4
      K1=1
      IF(NLINES.EQ.0)GO TO 170
      DO 160 I=1,NLINES
      K2=K1+3
      READ(5,171)(COEFF(II),II=K1,K2)
160   K1=K2+1
      IF(NREM.EQ.0)GO TO 174
170   READ(5,171)(COEFF(II),II=K1,NOIN)
171   FORMAT(4(F15.3,1X))
174   CONTINUE
C
C  CHECK ALL VARIABLES FOR VALIDITY
C
      IF(IOP.NE.ICHK(1))GO TO 100
      IF(MTLCD.NE.ICHK(2))GO TO 100
      IF(ITLCD.NE.ICHK(3))GO TO 100
      IF(RDACT.LT.RDMIN)GO TO 100
      IF(ADACT.LT.ADMIN)GO TO 100
      IF(RDACT.GT.RDMAX)GO TO 100
      IF(ADACT.GT.ADMAX)GO TO 100
C
C  CHECK RESTRAINTS OF MACHINE TOOL
C
      IF(FMIN.GT.FMTMAX)GO TO 100
      IF(FMAX.LT.FMTMIN)GO TO 100
      IF(VMIN.GT.VMTMAX)GO TO 100
      IF(VMAX.LT.VMTMIN)GO TO 100
C
C  MODEL IS VALID. COMPUT MIN COST,TIME
C
      NPTS=NPTS+1
      IF(VMAX.GT.VMTMAX)VMAX=VMTMAX
      IF(VMIN.LT.VMTMIN)VMIN=VMTMIN
      IF(FMAX.GT.FMTMAX)FMAX=FMTMAX
      IF(FMIN.LT.FMTMIN)FMIN=FMTMIN
      VINC=(VMAX-VMIN)/100.
      FINC=(FMAX-FMIN)/100.
      VV=VMIN-VINC
      FF=FMIN-FINC
      DO 180 I=1,101
      VV=VV+VINC
      FF=FF+FINC
      TT=XTL(VV,FF)
      CALL FEMEQN(FF,VV,TT,COST,TIME)
```

```
      IF(COST.GT.CMIN)GO TO 175
      CMIN=COST
      VMINC=VV
      FMINC=FF
      TMINC=TT
      ICFC=ICHK(4)
175   IF(TIME.GT.TMIN)GO TO 180
      TMIN=TIME
      VMINT=VV
      FMINT=FF
      TMINT=TT
      ICFT=ICHK(4)
180   CONTINUE
      GO TO 100
200   IF(NPTS.EQ.0)GO TO 210
      F(NDP+1)=FMINC
      V(NDP+1)=VMINC
      T(NDP+1)=TMINC
      ICF(NDP+1)=ICFC
      F(NDP+2)=FMINT
      V(NDP+2)=VMINT
      T(NDP+2)=TMINT
      ICF(NDP+2)=ICFT
      NDP3=2
      NDP=NDP+2
210   CONTINUE
      CALL RETURN(4HBASE)
      RETURN
      END
      OVERLAY(FRANK,16,0)
      PROGRAM PEMPRT
C  THIS PROGRAM PRINTS ALL DATA IN SUMMRY AND ON CRT
      COMMON/MTOOL/MTCODE,MTDES(15),RTV,FMT(50),VMT(50),TI,TO,HPMAX,XM
     1,FMTMIN,FMTMAX,VMTMIN,VMTMAX
      COMMON/TIME/XM0,XM1,XM2
      COMMON/MISC/ENDFIL,P,NL,PNAME(6),TLOAD,TO
      COMMON/OPN/IOP,OPNAME(6),IDUM
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3,
     1TF,TB,TS,IZ,D,G
      COMMON/COST/XK0,XK1,XK2,CFEED,CTOOL,CDULL,CDEP,CFRE,CBATCH
     1,CEFEED,CMFEED,CRESH,CSET,CLOAD,CRTV
      COMMON/MADA/F(20),V(20),T(20),ICF(20),NDF,NDF0,NDP1,NDP2,NDP3
      COMMON/OUTPUT/HP,R,PPT
C
C  CALL FEMEQN TO OBTAIN M&S AND K&S
C
      CALL FEMEQN(1.,1.,1.,C,TM)
C
C  WRITE TOOL,M/T CUT GEO., ETC INTO SUMMRY
C
      WRITE(4,500)(PNAME(I),I=1,6),(MTDES(I),I=1,15),(TLDES(I),I=1,15)
500   FORMAT(1H1,*CUT DESCRIPTION:*,T20,6A4/* MACHINE TOOL:*,T20,15A4/
     1* CUTTING TOOL:*,T20,15A4)
```

```
      WRITE(4,501)TO,TLOAD,NL
501   FORMAT(/* SETUP TIME(MIN):*,T26,F7.2,T40,*LOAD-UNLOAD TIME(MIN):*
     1,T65,F7.2,T80,*LOT SIZE:*,T90,I4)
      WRITE(4,502)RDACT,ADACT,XL,E,RDIST,VOL,VOLA
502   FORMAT(/* RADIAL DEPTH(IN):*,T29,F6.4,T40,*AXIAL DEPTH(IN):*,
     1T67,F6.3/* LENGTH METAL CUT(IN):*,T26,F7.2,T40,*EXTRA TRAVEL(IN):*
     1,T65,F7.2,T80,*RAPID TRVS DIST(IN):*,T101,F7.2/* VOLUME METAL*
     1* CUT(CU IN):*,T25,F8.2,T40,*VOLUME AIR CUT(CU IN):*,T64,F8.2)
      WRITE(4,503)XM0,XM1,XM2,XK0,XK1,XK2
503   FORMAT(/* M0:*,T5,F10.3,T40,*M1:*,T44,F10.3,T80,*M2:*,T84,F10.3/
     1* K0:*,T5,F10.3,T40,*K1:*,T44,F10.3,T80,*K2:*,T84,F10.3)
C  WRITE HEADER FOR COSTS ON CRT AND IN SUMMRY
C
      IF(NDPO.NE.0)WRITE(3,100)
      IF(NDPO.NE.0)WRITE(4,101)
100   FORMAT(//T30,*ON-LINE DATA ANALYSIS*/)
101   FORMAT(//T50,*ON-LINE DATA ANALYSIS*/)
141   WRITE(3,140)
  140 FORMAT(//1X,T18,*TOOL     CONST    FEED  TOOLING*
     1,*    TOTAL    PROD  PARTS*/*   FEED   SPEED  LIFE     COST      COST*
     2,*   COSTS     COST    TIME    PER    HP*/*   (IPT)  (FPM)  (MIN)*,
     3*    ($)      ($)     ($)      ($)     (MIN)  TOOL MAX*/*  ------   *
     4,2(*-----   *),3(*-------   *),*--------   ------   ----  ---*/)
C
C  WRTIE HEADER AND BASIC INFO INTO SUMMRY
C
      IF(NDPO.EQ.0)WRITE(4,143)
143   FORMAT(//,T50,*ANALYSIS OF DATA FROM MACHINABILITY FILES*)
      WRITE(4,600)
600   FORMAT(/1X,T36,*LOAD-*,T43,*RAPID*,T50,*EXTRA*,T57,*METAL*,
     1T65,*DULL*,T77,*TOOL*,T84,*TOOL*,T91,*TOTAL*,T98,*TOTAL*,
     2T110,*METAL*,T123,*TOTAL*)
      WRITE(4,601)
601   FORMAT(1X,T16,*TOOL*,T22,*CUTNG*,T28,*SETUP*,T36,*UNLD*,
     1T44,*TRVS*,T50,*TRAVEL*,T57,*CUTTING*,T65,*TOOL*,T71,*TOOL*,T77,
     2*RESHP*,T83,*PRESET*,T91,*PART*,T98,*PIECE*,T104,
     3*SPDL*,T110,*RMVL*,T116,*PARTS*,T123,*BATCH*)
      WRITE(4,602)
602   FORMAT(1X,*FEED*,T9,*SPEED*,T16,*LIFE*,T23,*FLD*,T28,
     1*COST*,T36,*COST*,T44,*COST*,T51,*COST*,T58,*COST*,T65,
     2*REPL*,T71,*DEPR*,T77,*COST*,T84,*COST*,T91,*COST*,
     3T98,*TIME*,T105,*HP*,T110,*RATE*,T117,*PER*,T123,*COST*)
      WRITE(4,603)
603   FORMAT(1X,*(IPT)*,T9,*(FPM)*,T16,*(MIN)*,T22,*CODE*,
     1T29,*($)*,T37,*($)*,T44,*($)*,T51,*($)*,T58,*($)*,T65,
     2*($)*,T71,*($)*,T78,*($)*,T84,*($)*,T91,*($)*,T98,*(MIN)*,
     3T105,*RAD*,T109,*(CIPM)*,T116,*TOOL*,T124,*($)*)
      WRITE(4,604)
604   FORMAT(1X,5(1H-),T8,7(1H-),T16,6(1H-),T23,3(1H-),T27,
     17(1H-),T35,7(1H-),T43,6(1H-),T50,6(1H-),T57,6(1H-),
     2T64,5(1H-),T70,6(1H-),T77,5(1H-),T83,5(1H-),T89,
     37(1H-),T97,7(1H-),T105,3(1H-),T109,6(1H-),T116,5(1H-),T122,8(1H-))
C
      DO 200 JJ=1,NDP
```

```
      CALL FEMEQN(F(JJ),V(JJ),T(JJ),C,TM)
C
C  WRITE FINAL OUTPUT TO CRT AND SUMMRY
C
147   FORMAT(/)
      IF(NDP0.NE.0)GO TO 149
      IF(NDP1.EQ.0)GO TO 148
      IF(JJ.EQ.4)WRITE(3,147)
      IF(JJ.EQ.4)WRITE(4,147)
      IF(JJ.EQ.6)WRITE(3,147)
      IF(JJ.EQ.6)WRITE(4,147)
      GO TO 149
148   IF(JJ.EQ.3)WRITE(3,147)
      IF(JJ.EQ.3)WRITE(4,147)
149   CONTINUE
C
      WRITE(3,150)F(JJ),V(JJ),T(JJ),XKO,CFEED,CTOOL,C,TM,PPT,HP
  150 FORMAT(2X,F6.4,2(2X,F5.0),3(2X,F6.2),2X,F7.2,2X,F6.1,2X,F4.1,
     12X,F3.0)
      WRITE(4,700)F(JJ),V(JJ),T(JJ),ICF(JJ),CSET,CLOAD,CRTV,CEFEED
     1,CMFEED,CDULL,CDEP,CRESH,CPRE,C,TM,HP,E,PPT,CBATCH
700   FORMAT(1X,F5.3,T8,F7.1,T16,F6.1,T23,I3,T27,
     1F7.2,T35,F7.2,T43,F6.2,T50,F6.2,T57,F6.2,T64,F5.2,T70,F6.2,
     2T77,F5.2,T83,F5.2,T89,F7.2,T97,F7.1,T104,F4.0,T109,F6.1,
     3T116,F5.1,T122,F8.2)
C  END OF DO LOOP FOR F,V,TL
C
200   CONTINUE
      IF(NDP0.NE.0)GO TO 320
      IF(NDP1.NE.0)GO TO 300
      WRITE(3,350)
      WRITE(4,350)
300   IF(NDP2.NE.0)GO TO 310
      WRITE(3,360)
      WRITE(4,360)
310   IF(NDP3.NE.0)GO TO 320
      WRITE(3,370)
      WRITE(4,370)
320   CONTINUE
350   FORMAT(/* THERE IS NO LEVEL 1 DATA*)
360   FORMAT(/* THERE IS NO LEVEL 2 DATA*)
370   FORMAT(/* THERE IS NO LEVEL 3 DATA*)
      RETURN
      END
      OVERLAY(FRANK,17,0)
      PROGRAM PEMONL
C
C  THIS PROGRAM ALLOWS FOR ON-LINE INPUT OF MACHINABILITY DATA
C
      COMMON/MADA/F(20),V(20),T(20),ICF(20),NDP,NDP0,NDP1,NDP2,NDP3
     1,TLIMIT,VMIN,VMAX,FMIN,FMAX
      COMMON/ANSR/IY,NO
      NDP0=0
100   WRITE(3,110)
```

```
110   FORMAT(/* ON-LINE INPUT OF F,V,T!   *)
      READ(2,120)IANS
120   FORMAT(A1)
      IF(IANS.EQ.IY)GO TO 150
      IF(IANS.EQ.NO)RETURN
      WRITE(3,130)
130   FORMAT(/* YES OR NO ONLY. TRY AGAIN.*/)
      GO TO 100
150   WRITE(3,160)
160   FORMAT(/* INPUT NO. DATA POINTS AND F(IPT),V(FPM),T(MIN)*
     1/* FOR EACH DATA POINT*/* =*)
      READ(2,*)NDP,(F(I),V(I),T(I),I=1,NDP)
      DO 170 I=1,NDP
170   ICF(I)=0
      NDPO=NDP
      RETURN
      END
      OVERLAY(FRANK,20,0)
      PROGRAM FAM
C
C  SUBROUTINE TO EVALUATE FACE MILLING
C
      WRITE(3,100)
100   FORMAT(* YOU ARE IN SUBROUTINE FAM*)
      RETURN
      END
      OVERLAY(FRANK,21,0)
      PROGRAM PKT
C
C  SUBROUTINE TO EVALUATE POCKETING
C
      WRITE(3,100)
100   FORMAT(* YOU ARE IN SUBROUTINE PKT*)
      RETURN
      END
      OVERLAY(FRANK,22,0)
      PROGRAM SLT
C
C  SUBROUTINE TO EVALUATE SLOTTING
C
      WRITE(3,100)
100   FORMAT(* YOU ARE IN SUBROUTINE SLT*)
      RETURN
      END
      OVERLAY(FRANK,15,0)
      PROGRAM CONTOUR
C
C  SUBROUTINE TO PRINT CONTOUR LINES AND CREATE F,V,TL ARRAY
C
      DIMENSION CLEVEL(10),PLEVEL(10)
      EXTERNAL XTL
      COMMON /ANSR/IY,NO
      COMMON/MADA/F(20),V(20),T(20),ICF(20),NDP,NDPO,NDP1,NDP2,NDP3
     1,TLIMIT,VMIN,VMAX,FMIN,FMAX
```

```
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      COMMON/COST/XK0,XK1,XK2,CFEED,CTOOL,CDULL,CDEF,CFRE,CBATCH
     1,CEFEED,CMFEED,CRESH,CSET,CLOAD,CRTV
      COMMON/TIME/XM0,XM1,XM2
      COMMON/TOOL/ITLCD,ITGRP,ITTYPE,TLDES(15),CP,CC,CW,K1,K2,K3,
     1TP,TB,TS,IZ,D,G
      XC(V,F)=XK0+XK1/XR(V,F)+XK2/XR(V,F)/XTL(V,F)
      XP(V,F)=XM0+XM1/XR(V,F)+XM2/XR(V,F)/XTL(V,F)
      XR(V,F)=12.*V*F*ADACT*RDACT*FLOAT(IZ)/D/3.14159
1     CONTINUE
      VLO=VMIN
      VHI=VMAX
      FLO=FMIN
      FHI=FMAX
201   CONTINUE
      CALL INITT(30)
79    WRITE(3,80)
80    FORMAT(/* DO YOU WANT TO CHANGE MAX. TOOL LIFE!  *)
      READ(2,101)IANS
      IF(IANS.EQ.IY)GO TO 81
      IF(IANS.EQ.NO)GO TO 89
      WRITE(3,110)
      GO TO 79
81    WRITE(3,82)
82    FORMAT(/* INPUT MAX. TOOL LIFE (0=NO LIMIT)*/* =*)
      READ(2,*)TLIMIT
89    NNLC=-5
      NNLT=-5
90    WRITE(3,100)
100   FORMAT(/* DO YOU WANT TO CHOOSE CONTOUR LINES!  *)
      READ(2,101)IANS
101   FORMAT(A1)
      IF(IANS.EQ.IY)GO TO 120
      IF(IANS.EQ.NO)GO TO 150
      WRITE(3,110)
110   FORMAT(/* YES OR NO ONLY.  LET&S TRY AGAIN*)
      GO TO 90
120   WRITE(3,121)
121   FORMAT(* COST(1), TIME(2), OR BOTH(3)*/* =*)
      READ(2,*)IWHICH
      IF(IWHICH.EQ.2)GO TO 140
      WRITE(3,130)
130   FORMAT(/* INPUT NO. CONTOURS AND COSTS*/* =*)
      READ(2,*)NNLC,(CLEVEL(I),I=1,NNLC)
      IF(IWHICH.NE.3)GO TO 150
140   WRITE(3,141)
141   FORMAT(/* INPUT NO. CONTOURS AND TIMES*/* =*)
      READ(2,*)NNLT,(PLEVEL(I),I=1,NNLT)
150   CALL INITT(30)
      CALL VWINDO(0.,8.,0.,8.)
      CALL SWINDO(200,800,200,560)
      CALL CONTR(XTL,VLO,VHI,FLO,FHI,90., NNLC,CLEVEL,0,XK0,XK1,XK2,
     1RDACT,ADACT,IZ,D,TLIMIT)
      CALL CONTR(XTL,VLO,VHI,FLO,FHI,90., NNLT,PLEVEL,56,XM0,XM1,XM2,
```

```
     1RDACT,ADACT,IZ,0,TLIMIT)                                          011330
      CALL VWINDO(VLO,VHI-VLO,FLO,FHI-FLO)                              011340
      XDIF=VHI-VLO                                                      011350
      DO 320 I=1,20                                                     011360
      II=11-I                                                           011370
      XDIV=5.*10.**II                                                   011380
      IF(XDIF/XDIV.GE.4.)GO TO 323                                      011390
      XDIV=2.5*10.**II                                                  011400
      IF(XDIF/XDIV.GE.4.)GO TO 323                                      011410
      XDIV=2.*10.**II                                                   011420
      IF(XDIF/XDIV.GE.4.)GO TO 323                                      011430
      XDIV=1.*10.**II                                                   011440
      IF(XDIF/XDIV.GE.4.)GO TO 323                                      011450
320   CONTINUE                                                          011460
323   IXNUM=INT(XDIF/XDIV)                                              011470
      DO 335 I=1,10001                                                  011480
      II=I-1         IF(XDIV*II.GE.VLO)GO TO 334
335   CONTINUE                                                          011510
334   GVLO=XDIV*II                                                      011520
      YDIF=FHI-FLO                                                      011530
      DO 420 I=1,20                                                     011540
      II=11-I                                                           011550
      YDIV=5.*10.**II                                                   011560
      IF(YDIF/YDIV.GE.4.)GO TO 423                                      011570
      YDIV=2.5*10.**II                                                  011580
      IF(YDIF/YDIV.GE.4.)GO TO 423                                      011590
      YDIV=2.*10.**II                                                   011600
      IF(YDIF/YDIV.GE.4.)GO TO 423                                      011610
      YDIV=1.*10.**II                                                   011620
      IF(YDIF/YDIV.GE.4.)GO TO 423                                      011630
420   CONTINUE                                                          011640
423   IYNUM=INT(YDIF/YDIV)                                              011650
      DO 435 I=1,10001                                                  011660
      II=I-1                                                            011670
      IF(YDIV*II.GE.FLO)GO TO 434                                       011680
435   CONTINUE                                                          011690
434   GFLO=YDIV*II                                                      011700
      CALL MOVABS(200,200)                                              011710
      DO 400 I=1,10                                                     011720
      IF((I-1)*XDIV+GVLO.GT.VHI)GO TO 405                               011730
      CALL DRAWA((I-1)*XDIV+GVLO,FLO)                                   011740
      CALL DRWREL(0,-10)                                                011750
      CALL MOVREL(-25,-20)                                              011760
      CALL NUUMB(GVLO+(I-1)*XDIV,0)                                     011770
      CALL MOVREL(25,30)                                                011780
400   CONTINUE                                                          011790
405   CALL DRAWA(VHI,FLO)                                               011800
      CALL MOVABS(200,200)                                              011810
      DO 500 I=1,10                                                     011820
      IF((I-1)*YDIV+GFLO.GT.FHI)GO TO 505                               011830
      CALL DRAWA(VLO,(I-1)*YDIV+GFLO)                                   011840
      CALL DRWREL(-10,0)                                                011850
      CALL MOVREL(-75,-5)                                               011860
      CALL NUUMB(GFLO+(I-1)*YDIV,4)                                     011870
```

```
500   CALL MOVREL(85,5)
505   CALL DRAWA(VLO,FHI)
      CALL MOVABS(0,550)
      CALL ANMODE
      WRITE(3,501)
501   FORMAT(1X,'F'/1X,'E'/1X,'E'/1X,'D')
      CALL MOVABS(550,175)
      CALL ANMODE
      WRITE(3,986)
986   FORMAT(/35X,*SPEED*)
      WRITE(3,1001)(CLEVEL(I),I=1,5)
1001  FORMAT(/14X,'COST ($) -',1X,'A=',F6.2,2X,'B=',F6.2,2X,'C=',
     1F6.2,2X,'D=',F6.2,2X,'E=',F6.2)
      WRITE(3,1002)(PLEVEL(I),I=1,5)
1002  FORMAT(1X,'PRODUCTION TIME (MIN) -',1X,'1=',F6.2,2X,
     1'2=',F6.2,2X,'3=',F6.2,2X,'4=',F6.2,2X,'5=',F6.2)
      WRITE(3,1003)TLIMIT
1003  FORMAT(* MAX TOOL LIFE=*,F5.1,5X,*SOLID=COST      DASHED=TIME*)
      CALL VCURSR(ICHAR,VLO,FLO)
      CALL VCURSR(ICHAR,VHI,FHI)
      IF(VLO.GE.VHI.AND.FLO.GE.FHI)GO TO 1
      WRITE(3,1004)
1004  FORMAT(1X,'REDRAW WITH NEW LIMITS ! ')
      READ(2,1005)IANS
1005  FORMAT(A1)
      IF(IANS.EQ.IY)GO TO 201
      RETURN
      END
      SUBROUTINE NDUMB(X,NDEC)
      CALL ANMODE
      IFIRST=0
      IF(X)3,5,5
3     CALL TOUTPT(45)
      X=-X
5     X=X+.5*10.**(-NDEC)
      DO 100 I=1,10
      IEX=10-I
      ITEMP=INT(X/10.**IEX)
      IF(IFIRST)10,10,20
10    IF(ITEMP)100,100,20
20    CALL TOUTPT(ITEMP+48)
      X=X-(ITEMP*10.**IEX)
      IFIRST=1
100   CONTINUE
      CALL TOUTPT(46)
      IF(NDEC)999,999,30
30    DO 200 I=1,NDEC
      IF(NDEC)999,999,30
      CALL TOUTPT(ITEMP+48)
      X=X-(ITEMP*10.**(-I))
200   CONTINUE
999   RETURN
      END
      SUBROUTINE CONTR(Q,QXL,QXU,QYL,QYU,A,NNL,ZLEVEL,IDASH,
```

```
     1XK0,XK1,XK2,RDACT,ADACT,IZ,D,TLIMIT)
      DIMENSION XSTR(2000),YSTR(2000),T(2),ZLEVEL(1)
      F(V,F)=QQ(QXL+V*(QXU-QXL)/8.,QYL+F*(QYU-QYL)/8.)
      QQ(V,F)=XK0+XK1/XR(V,F)+XK2/Q(V,F)/XR(V,F)
      XR(V,F)=12.*V*F*RDACT*ADACT*FLOAT(IZ)/D/3.14159
      NL=IABS(NNL)
      YL=0.
      YU=8.
      XL=0.
      XU=8.
      XLIM=8.
      YLIM=8.
      XNL=NL
      PLANE=1.
      IF(A.EQ.90.) PLANE=0.
      SA=1.
      CA=0.
      ZMIN=F(XL,YL)
      ZMAX=ZMIN
      XDIF=(XU-XL)/20.
      YDIF=(YU-YL)/20.
      DO 10 I=1,21
      DO 10 J=1,21
      Z=F((I-1.)*XDIF+XL, (J-1.)*YDIF+YL)
      ZMIN=AMIN1(ZMIN,Z)
   10 ZMAX=AMAX1(ZMAX,Z)
      DZ=(ZMAX-ZMIN)/XNL
      PLANE=PLANE*(XU-XL+YU-YL)/(4.*(ZMAX-ZMIN))
      SF=AMIN1(XLIM/(XU-XL+(YU-YL)*CA), YLIM/((YU-YL)*SA+(ZMAX-ZMIN)*PLA
     1NE))
      DELT=(XU-XL+YU-YL)*.01
C     DRAW CONTOURS AT NL LEVELS
      DO 70 M=1,NL
      ZC=DZ*(M-.5)+ZMIN
      IF(NNL.GT.0)ZC=ZLEVEL(M)
      IF(NNL.LT.0)ZLEVEL(M)=ZC
      XSTR(1)=2.*XL-XU
      YSTR(1)=2.*YL-YU
      J=0
C     SCAN X-Y PLANE FOR ACCEPTABLE STARTING POINT FOR A CONTOUR.
      DO 70 LX=1,21
   30 X=XL+XDIF*(LX-1.)
      Z1=F(X,YL)
      DO 70 LY=1,20
      X=XL+XDIF*(LX-1.)
      Y=YL+YDIF*(LY)
      Z2=F(X,Y)
      IF((Z1-ZC)*(Z2-ZC).LE.0.) GO TO 32
      Z1=Z2
      GO TO 70
   32 Z1=Z2
      XM=X-XDIF
      XP=X+XDIF
      YM=Y-YDIF
```

```
      YP=Y
      IF(J)39,141,39
39    DO 40 I=1,J
      IF(XSTR(I).GE.XM.AND.XSTR(I).LE.XP.AND.YSTR(I).GE.YM.AND.YSTR(I).L
     1E.YP)GO TO 70
40    CONTINUE
141   CONTINUE
C     ACCEPTABLE POINT FOUND
      REF=F(X,YM)-ZC
      DO 43 IC=1,20
      Y=(YM+YP)*.5
      IF(REF*(F(X,Y)-ZC))42,44,41
41    YM=Y
      GO TO 43
42    YP=Y
43    CONTINUE
C     MOVE PEN TO STARTING POINT
44    CALL MOVEA((X-XL+(Y-YL)*CA)*SF,((ZC-ZMIN)*PLANE+(Y-YL)*SA)*SF)
      CALL MOVREL(3,5)
      CALL ANMODE
      IF(IDASH.EQ.0)CALL TOUTPT(64+M)
      IF(IDASH.NE.0)CALL TOUTPT(48+M)
      CALL MOVEA((X-XL+(Y-YL)*CA)*SF,((ZC-ZMIN)*PLANE+(Y-YL)*SA)*SF)
      X1=X-DELT
      X2=X+DELT
      Y1=Y-DELT
      Y2=Y+DELT
C     COMPUTE PARTIAL DERIVATIVES FOR INITIAL DIRECTION.
      FXM=F(X-.0002,Y)
      FXM2=F(X+.0002,Y)
      FXM3=F(X+.0001,Y)
      FXM4=F(X-.0001,Y)
      FYM1=F(X,Y-.0002)
      FYM2=F(X,Y+.0002)
      FYM3=F(X,Y+.0001)
      FYM4=F(X,Y-.0001)
      DX=250.*(FXM-FXM2+8.*(FXM3-FXM4))
      DY=250.*(FYM1-FYM2+8.*(FYM3-FYM4))
      IF(DX.EQ.0.0.AND.DY.EQ.0.0)GO TO 65
      R=1.
      IF(DY.GE.0.)R=-1.
      IBACK=0
      XIN=X
      YIN=Y
46    J=J+1
      XSTR(J)=X+DY*DELT*R
      YSTR(J)=Y-DX*DELT*R
C     COMPUTE NEXT POINTS ON CONTOUR
      ILOOP=0
      DO 60 I=1,500
      IF(X.EQ.XSTR(J).AND.Y.EQ.YSTR(J))GO TO 49
      DELX=(X-XSTR(J))/SQRT((X-XSTR(J))**2+(Y-YSTR(J))**2)*DELT
      DELY=(Y-YSTR(J))/SQRT((X-XSTR(J))**2+(Y-YSTR(J))**2)*DELT
      J=J+1
```

```
      XSTR(J)=X
      YSTR(J)=Y
      X=X+DELX
      Y=Y+DELY
      XC1=X+DELY
      XC2=X-DELY
      YC1=Y-DELX
      YC2=Y+DELX
      LC=1
      IF(F(XC1,YC1).LE.ZC)LC=-1
      IF((F(XC2,YC2)-ZC)*LC.LE.0.)GO TO 50
C     DISCONTINUITY REACHED
49    CALL TOUTPT(64)
      GO TO 58
50    DO 55 IC=1,10
      IF((F(X,Y)-ZC)*LC)53,56,52
52    XC1=X
      YC1=Y
      GO TO 54
53    XC2=X
      YC2=Y
54    X=(XC1+XC2)*.5
      Y=(YC1+YC2)*.5
55    CONTINUE
56    IF(IDASH)105,105,103
103   CALL DASHA((X-XL+(Y-YL)*CA)*SF,((ZC-ZMIN)*PLANE+(Y-YL)*SA)*SF,IDAS
     1H)
      GO TO 104
105   CALL DRAWA((X-XL+(Y-YL)*CA)*SF,((ZC-ZMIN)*PLANE+(Y-YL)*SA)*SF)
104   IF(ILOOP)156,156,65
156   IF(X.GE.X1.AND.X.LE.X2.AND.Y.GE.Y1.AND.Y.LE.Y2.AND.I.GE.4)ILOOP=1
      IF(X.GE.XL.AND.X.LE.XU.AND.Y.GE.YL.AND.Y.LE.YU)GO TO 60
58    IF(IBACK.GE.1)GO TO 65
      IBACK=1
      R=-R
      X=XIN
      Y=YIN
      CALL MOVEA((X-XL+(Y-YL)*CA)*SF,((ZC-ZMIN)*PLANE+(Y-YL)*SA)*SF)
      GO TO 48
60    CONTINUE
65    CONTINUE
70    CONTINUE
      RETURN
      END
      OVERLAY(FRANK,23,0)
      PROGRAM PEMCUT
C
C  THIS PROGRAM READS CUT GEOMETRY FOR PERIPHERAL END MILLING
C
      COMMON/CUTS/VOLA,VOL,XL,RDIST,E,RDACT,ADACT
      WRITE(3,100)
100   FORMAT(/* INPUT:*,T10,*TOTAL LENGTH OF CUT (IN),*/T10,
     1*RAPID TRAVERSE DISTANCE (IN),*/T10,*EXTRA TRAVEL (IN),*/
     2T10,*RADIAL DEPTH (IN),*/T10,*AXIAL DEPTH (IN)*/* =*)
```

```
      READ(2,*)XL,HDIST,E,HDACT,ADACT                              014010
      RETURN                                                       014020
      END                                                          014030
```

$$

APPENDIX F

INPUT AND OUTPUT SEQUENCE FOR

MICRO PROGRAM

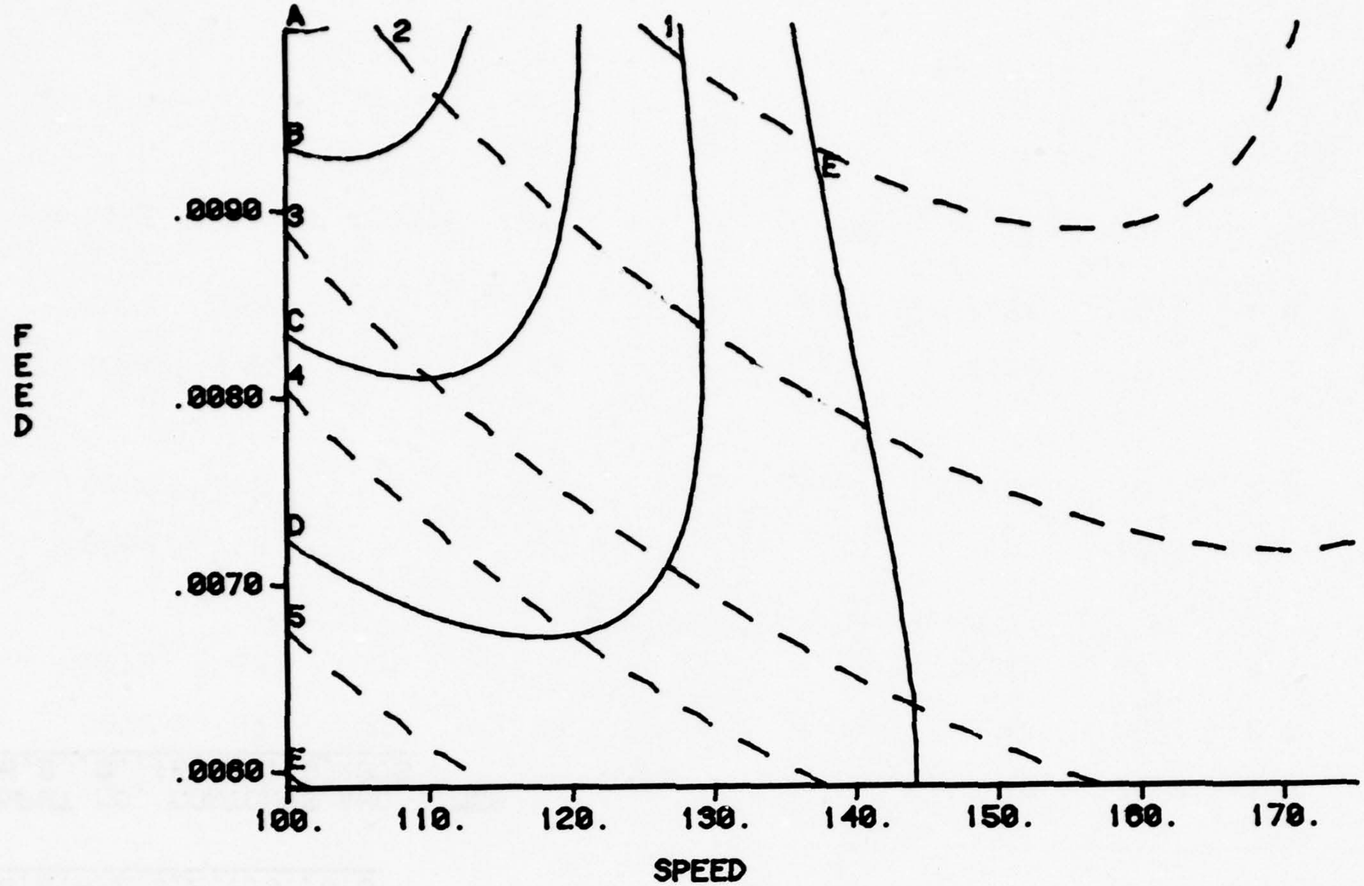
(User Responses Underlined)

```
                MICRO COST ESTIMATION SYSTEM
          DEVELOPED BY METCUT RESEARCH ASSOC. INC.

INPUT DATA BASE INITIALS
=MAC

INPUT PART NAME (MAX 24 CHAR)
=FIN MLL PERIPH SD B

INPUT NO. PARTS MACHINED AT ONE TIME ON M/T
=3

INPUT WORKPIECE MATL CODE (0=LISTING)
=64001

CODE 64001 IS 6AL-4V TITANIUM  MIL-F-83142  COMP. 6  COND. A
CORRECT?  Y

INPUT OPERATION CODE (0=LIST)
=72

CODE  72 IS PERIPHERAL END MILLING
CORRECT?  Y
```

```
INPUT TOOL CODE (0=LIST)
=12430

CODE 12430 IS 1"DIA X 2" X 4FL X .12CR NEW END MILL
CORRECT?  Y

INPUT UNIT HP
=1.9

INPUT M/T CODE (0=LIST)
=54000

CODE 54000 IS CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CORRECT?  Y

INPUT:  SETUP TIME (MIN),
        LOAD-UNLOAD TIME (MIN),
        LOT SIZE
=0.,0.,20
```

```
INPUT:  TOTAL LENGTH OF CUT (IN),
        RAPID TRAVERSE DISTANCE (IN),
        EXTRA TRAVEL (IN),
        RADIAL DEPTH (IN),
        AXIAL DEPTH (IN)
=122.6,124.4,6.9,.1,1.

INPUT MAX TOOL LIFE (0=NO LIMIT)
=0.

CONTOUR PLOT?  Y
```

```
DO YOU WANT TO CHOOSE CONTOUR LINES? Y

COST(1), TIME(2), OR BOTH(3)
=3

INPUT NO. CONTOURS AND COSTS
=5,2.4,2.5,2.7,3.,3.5

INPUT NO. CONTOURS AND TIMES
=5,8.,9.,10.5,11.5,13.5
```



COST ($) - A= 2.40 B= 2.50 C= 2.70 D= 3.00 E= 3.50
PRODUCTION TIME (MIN) - 1= 8.00 2= 9.00 3= 10.50 4= 11.50 5= 13.50
MAX TOOL LIFE= 0.0 SOLID=COST DASHED=TIME

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CONST COST ($)	FEED COST ($)	TOOLING COSTS ($)	TOTAL COST ($)	PROD TIME (MIN)	PARTS PER TOOL	HP MAX
.0070	52.	30.	.20	5.20	8.18	13.58	28.2	1.4	1
.0070	52.	60.	.20	5.20	4.09	9.49	25.1	2.7	1
.0070	52.	90.	.20	5.20	2.73	8.13	24.7	4.1	1
.0060	150.	135.	.20	2.12	.74	3.06	10.5	15.1	3
.0060	200.	15.	.20	1.59	5.00	6.79	9.3	2.2	3
.0049	145.	171.	.20	2.70	.75	3.64	13.1	15.1	2
.0073	183.	10.	.20	1.44	6.88	8.52	9.1	1.6	4

ON-LINE INPUT OF F,V,T?

APPENDIX G

OUTPUT FROM MICRO-ECONOMIC ANALYSIS PROGRAM

FOR ALL ROUGH AND FINISH CUTS ON F-15 FORMER-UPPER PANELS

CUT DESCRIPTION: MILL TOOLNG SURF SD B
MACHINE TOOL: CINCINNATI 3-SPINDLE-20 MEDIUM N/C PROFILER
CUTTING TOOL: 2'DIA X 2' X AFL X .12CR ROUGHING END MILL

SETUP TIME(MIN): 108.00 LOAD-UNLOAD TIME(MIN): 13.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.9700 AXIAL DEPTH(IN): 1.000
LENGTH METAL CUT(IN): 456.90 EXTRA TRAVEL(IN): 22.00 RAPID TRVS DIST(IN): 419.20
VOLUME METAL CUT(CU IN) 900.09 VOLUME AIR CUT(CU IN): 43.34

MO: 21.354 M1: 963.433 M2: 2700.279
K0: 4.324 K1: 192.880 K2: 32920.402

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.008	50.3	30.0	0	1.10	2.66	.61	.98	20.26	2.03	101.84	17.15	0.00	146.62	135.2	12.	9.1	.3	2932.47
.008	50.3	60.0	0	1.10	2.66	.61	.98	20.26	1.01	50.92	8.57	0.00	86.12	130.3	12.	9.1	.6	1722.30
.006	50.3	90.0	0	1.10	2.66	.61	.98	20.26	.68	33.95	5.72	0.00	65.95	128.6	12.	9.1	.9	1318.91

CUT DESCRIPTION: ROUGH MLL RIB TOPS SD A
MACHINE TOOL: CINCINNATI 3-SPINDLE-20 MEDIUM N/C PROFILER
CUTTING TOOL: 1'DIA X 2' X AFL R/H ROUGHING

SETUP TIME(MIN): 108.00 LOAD-UNLOAD TIME(MIN): 13.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.0000 AXIAL DEPTH(IN): 1.000
LENGTH METAL CUT(IN): 182.30 EXTRA TRAVEL(IN): 19.20 RAPID TRVS DIST(IN): 265.20
VOLUME METAL CUT(CU IN) 182.30 VOLUME AIR CUT(CU IN): 19.20

MO: 20.254 M1: 201.500 M2: 546.900
K0: 4.149 K1: 41.196 K2: 3292.186

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.007	54.5	30.0	0	1.10	2.66	.39	.67	6.39	.64	11.00	7.19	0.00	30.04	58.0	8.	5.8	1.0	600.87
.007	54.5	60.0	0	1.10	2.66	.39	.67	6.39	.32	5.50	3.59	0.00	20.43	56.4	8.	5.8	1.9	412.00
.007	54.5	90.0	0	1.10	2.66	.39	.67	6.39	.21	3.67	2.40	0.00	17.49	55.9	8.	5.8	2.9	349.84

CUT DESCRIPTION: RGH MLL TOOLNG SURF SD A
MACHINE TOOL: CINCINNATI 3-SPINDLE-20 MEDIUM N/C PROFILER
CUTTING TOOL: 2"DIA X 2" X 6FL X .12CR ROUGHING END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.7700 AXIAL DEPTH(IN): .860
LENGTH METAL CUT(IN): 467.70 EXTRA TRAVEL(IN): 33.80 RAPID TRVS DIST(IN): 420.90
VOLUME METAL CUT(CU IN) 712.09 VOLUME AIR CUT(CU IN): 51.45

M0: 3.066 M1: 763.536 M2: 2136.255
K0: .615 K1: 156.161 K2: 26090.800

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP ROD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.012	50.3	30.0	0	0.00	0.00	.61	1.00	13.83	1.38	69.52	11.70	0.00	98.04	82.3	14.	10.5	.6	1960.86
.012	50.3	60.0	0	0.00	0.00	.61	1.00	13.83	.69	34.76	5.85	0.00	56.74	78.9	14.	10.5	.9	1134.84
.012	50.3	90.0	0	0.00	0.00	.61	1.00	13.83	.46	23.17	3.90	0.00	42.97	77.8	14.	10.5	1.3	859.50

CUT DESCRIPTION: ROUGH MILL PERIPH SD B
MACHINE TOOL: CINCINNATI 3-SPINDLE-20 MEDIUM N/C PROFILER
CUTTING TOOL: 2"DIA X 4" X 6FL X .12CR ROUGHING END MILL

SETUP TIME(MIN): 108.00 LOAD-UNLOAD TIME(MIN): 13.00 LOT SIZE: 20

RADIAL DEPTH(IN): .8000 AXIAL DEPTH(IN): 1.600
LENGTH METAL CUT(IN): 133.60 EXTRA TRAVEL(IN): 12.50 RAPID TRVS DIST(IN): 176.50
VOLUME METAL CUT(CU IN) 171.01 VOLUME AIR CUT(CU IN): 16.00

M0: 19.661 M1: 187.008 M2: 513.024
K0: 4.020 K1: 38.233 K2: 7326.410

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP ROD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.011	50.3	30.0	0	1.10	2.66	.26	.40	4.31	.43	26.64	3.02	0.00	38.82	44.8	11.	8.1	1.4	776.44
.011	50.3	60.0	0	1.10	2.66	.26	.40	4.31	.22	13.32	1.51	0.00	23.78	43.8	11.	8.1	2.8	475.53
.011	50.3	90.0	0	1.10	2.66	.26	.40	4.31	.14	8.88	1.01	0.00	18.76	43.4	11.	8.1	4.3	375.22

CUT DESCRIPTION: RGH MLL POCKTS SD B
MACHINE TOOL: CINCINNATI 3-SPINDLE-20 MEDIUM N/C PROFILER
CUTTING TOOL: 1.5"DIA X 3" X 6FL X .19CR CHIPBREAKER END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.4700 AXIAL DEPTH(IN): 1.200
LENGTH METAL CUT(IN): 230.00 EXTRA TRAVEL(IN): 23.30 RAPID TRVS DIST(IN): 376.20
VOLUME METAL CUT(CU IN): 405.72 VOLUME AIR CUT(CU IN): 41.10

MO: 2.667 M1: 446.821 M2: 1217.160
KO: .569 K1: 91.350 K2: 11795.971

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.008	45.6	30.0	0	0.00	0.00	.55	.85	8.44	.84	26.91	12.24	0.00	49.83	52.3	13.	9.8	.7	996.64
.008	45.6	60.0	0	0.00	0.00	.55	.85	8.44	.42	13.46	6.12	0.00	29.84	50.2	13.	9.8	1.5	596.72
.008	45.6	90.0	0	0.00	0.00	.55	.85	8.44	.28	8.97	4.08	0.00	23.17	49.5	13.	9.8	2.2	463.42

CUT DESCRIPTION: RGH MLL RIB TOPS SD B
MACHINE TOOL: CINCINNATI 3-SPINDLE-20 MEDIUM N/C PROFILER
CUTTING TOOL: 1"DIA X 2" X 4FL B/N ROUGHING

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .9800 AXIAL DEPTH(IN): .700
LENGTH METAL CUT(IN): 66.10 EXTRA TRAVEL(IN): 9.80 RAPID TRVS DIST(IN): 138.60
VOLUME METAL CUT(CU IN): 45.34 VOLUME AIR CUT(CU IN): 6.72

MO: .990 M1: 52.067 M2: 136.034
KO: .202 K1: 10.665 K2: 818.886

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.007	54.5	30.0	0	0.00	0.00	.20	.34	2.32	.23	3.99	2.61	0.00	9.69	15.1	5.	4.0	2.6	193.82
.007	54.5	60.0	0	0.00	0.00	.20	.34	2.32	.12	1.99	1.30	0.00	6.28	14.6	5.	4.0	5.3	125.55
.007	54.5	90.0	0	0.00	0.00	.20	.34	2.32	.08	1.33	.87	0.00	5.14	14.4	5.	4.0	7.9	102.80

CUT DESCRIPTION: FIN MLL RB " FLNG TP SD
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1'DIAX2'X4FLX.25CR .06 UNDERSIZE END MILL

SETUP TIME(MIN): 90.00 LOAD-UNLOAD TIME(MIN): 7.00 LOT SIZE: 20

RADIAL DEPTH(IN): .9400 AXIAL DEPTH(IN): .100
LENGTH METAL CUT(IN): 126.00 EXTRA TRAVEL(IN): 17.90 RAPID TRVS DIST(IN): 265.50
VOLUME METAL CUT(CU IN) 11.84 VOLUME AIR CUT(CU IN): 1.68

MU: 13.396 M1: 13.527 M2: 35.532
KU: 3.016 K1: 3.043 K2: 241.420

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.006	55.4	30.0	0	1.01	1.58	.43	.79	5.58	.56	9.86	6.44	0.00	26.25	44.2	1.	.5	1.2	524.92
.006	55.4	60.0	0	1.01	1.58	.43	.79	5.58	.28	4.93	3.22	0.00	17.83	43.0	1.	.5	2.4	[illegible]
.006	55.4	90.0	0	1.01	1.58	.43	.79	5.58	.19	3.29	2.15	0.00	15.01	42.6	1.	.5	3.6	300.16

CUT DESCRIPTION: FIN MLL PKT FLOORS SD A
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1.25'DIA X 2' X 6FL X .12CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.0800 AXIAL DEPTH(IN): 1.370
LENGTH METAL CUT(IN): 521.40 EXTRA TRAVEL(IN): 34.40 RAPID TRVS DIST(IN): 436.70
VOLUME METAL CUT(CU IN) 771.46 VOLUME AIR CUT(CU IN): 50.90

MU: 3.119 M1: 822.362 M2: 2314.390
KU: .702 K1: 185.031 K2: 16875.763

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.007	49.1	30.0	0	0.00	0.00	.70	1.23	18.62	1.86	38.27	20.20	0.00	80.88	99.6	12.	9.3	.4	1617.57
.007	49.1	60.0	0	0.00	0.00	.70	1.23	18.62	.93	19.13	10.10	0.00	50.73	95.5	12.	9.3	[illegible]	[illegible]
.007	49.1	90.0	0	0.00	0.00	.70	1.23	18.62	.62	12.76	6.73	0.00	40.66	94.1	12.	9.3	1.1	813.15

CUT DESCRIPTION: MILL TOOLING PADS SD A
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1.25"DIA X 2" X 6FL X .12CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.0000
LENGTH METAL CUT(IN): 46.10
VOLUME METAL CUT(CU IN) 4.61
AXIAL DEPTH(IN): .100
EXTRA TRAVEL(IN): 7.20
VOLUME AIR CUT(CU IN): .72
RAPID TRVS DIST(IN): 134.80

MU: .963 M1: 5.330 M2: 13.830
KU: .212 K1: 1.199 K2: 100.844

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP ROD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.006	49.1	30.0	0	0.00	0.00	.22	.30	1.92	.19	3.95	2.08	0.00	8.66	11.7	1.	.5	3.5	173.20
.006	49.1	60.0	0	0.00	0.00	.22	.30	1.92	.10	1.97	1.04	0.00	5.55	11.3	1.	.5	7.0	110.97
.006	49.1	90.0	0	0.00	0.00	.22	.30	1.92	.06	1.32	.69	0.00	4.51	11.1	1.	.5	10.5	90.23

CUT DESCRIPTION: FIN MLL PKT WALLS SD A
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 3/4"DIA X 2" X 4FL X .09CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .0700
LENGTH METAL CUT(IN): 262.80
VOLUME METAL CUT(CU IN) 28.15
AXIAL DEPTH(IN): 1.530
EXTRA TRAVEL(IN): 26.90
VOLUME AIR CUT(CU IN): 2.88
RAPID TRVS DIST(IN): 432.00

MU: 3.066 M1: 31.027 M2: 84.438
KU: .694 K1: 6.981 K2: 439.123

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP ROD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.004	57.0	30.0	0	0.00	0.00	.69	1.30	12.73	1.27	14.54	13.61	0.00	44.15	71.1	1.	.5	.5	883.05
.004	57.0	60.0	0	0.00	0.00	.69	1.30	12.73	.64	7.27	6.81	0.00	29.44	68.3	1.	.5	1.1	588.80
.004	57.0	90.0	0	0.00	0.00	.69	1.30	12.73	.42	4.85	4.54	0.00	24.54	67.3	1.	.5	1.6	490.72

CUT DESCRIPTION: FORM CRNR " FLT RDI SD A
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1/2'DIA X 3' X 6FL X .09CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .0700 AXIAL DEPTH(IN): .940
LENGTH METAL CUT(IN): 116.20 EXTRA TRAVEL(IN): 17.50 RAPID TRVS DIST(IN): 49.60
VOLUME METAL CUT(CU IN): 7.65 VOLUME AIR CUT(CU IN): 2.15

M0: .354 M1: 8.797 M2: 22.938
K0: .080 K1: 1.929 K2: 105.049

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.005	52.4	30.0	0	0.00	0.00	.08	.49	3.27	.33	2.97	3.35	0.00	10.48	18.5	1.	.5	2.1	209.68
.005	52.4	60.0	0	0.00	0.00	.08	.49	3.27	.16	1.48	1.68	0.00	7.16	[illegible]	1.	.5	[illegible]	[illegible]
.005	52.4	90.0	0	0.00	0.00	.08	.49	3.27	.11	.99	1.12	0.00	6.05	17.5	1.	.5	6.2	121.06

CUT DESCRIPTION: FIN MLL FLNG TOPS SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1.25'DIA X 3' X 6FL X .12CR NEW END MILL

SETUP TIME(MIN): 90.00 LOAD-UNLOAD TIME(MIN): 7.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.2500 AXIAL DEPTH(IN): .100
LENGTH METAL CUT(IN): 118.10 EXTRA TRAVEL(IN): 4.70 RAPID TRVS DIST(IN): 49.60
VOLUME METAL CUT(CU IN): 14.76 VOLUME AIR CUT(CU IN): .59

M0: 11.654 M1: 15.350 M2: 44.288
K0: 2.667 K1: 3.454 K2: 340.390

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.006	55.7	30.0	0	1.01	1.58	.08	.17	4.34	.43	9.56	5.69	0.00	22.86	33.8	1.	.8	1.6	457.21
.006	55.7	60.0	0	1.01	1.58	.08	.17	4.34	.22	4.78	2.85	0.00	15.02	[illegible]	1.	.8	[illegible]	[illegible]
.006	55.7	90.0	0	1.01	1.58	.08	.17	4.34	.14	3.19	1.90	0.00	12.40	32.5	1.	.8	4.7	248.09

CUT DESCRIPTION: SEMI-FIN PERIPH SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1.25"DIA X 3" X 6FL X .12CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .1900 AXIAL DEPTH(IN): 1.820
LENGTH METAL CUT(IN): 67.60 EXTRA TRAVEL(IN): 6.30 RAPID TRVS DIST(IN): 61.60
VOLUME METAL CUT(CU IN) 23.38 VOLUME AIR CUT(CU IN): 2.18

M0: .440 M1: 25.555 M2: 70.128
K0: .059 K1: 5.750 K2: 570.669

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.008	55.7	30.0	0	0.00	0.00	.10	.17	1.86	.19	4.10	2.44	0.00	8.87	10.3	4.	2.8	3.6	177.35
.008	55.7	60.0	0	0.00	0.00	.10	.17	1.86	.09	2.05	1.22	0.00	5.50	[illegible]	4.	2.8	7.3	110.02
.008	55.7	90.0	0	0.00	0.00	.10	.17	1.86	.06	1.37	.81	0.00	4.38	9.8	4.	2.8	10.9	87.57

CUT DESCRIPTION: FIN MLL PERIPH SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1.25"DIA X 3" X 6FL X .12CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .0300 AXIAL DEPTH(IN): 1.820
LENGTH METAL CUT(IN): 65.90 EXTRA TRAVEL(IN): 6.40 RAPID TRVS DIST(IN): 64.60
VOLUME METAL CUT(CU IN) 3.60 VOLUME AIR CUT(CU IN): .35

M0: .461 M1: 3.948 M2: 10.794
K0: .104 K1: .888 K2: 87.840

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.008	55.7	30.0	0	0.00	0.00	.10	.18	1.81	.18	4.00	2.38	0.00	8.66	10.1	1.	.4	3.7	173.18
.008	55.7	60.0	0	0.00	0.00	.10	.18	1.81	.09	2.00	1.19	0.00	5.38	9.7	1.	.4	7.4	107.56
.008	55.7	90.0	0	0.00	0.00	.10	.18	1.81	.06	1.33	.79	0.00	4.28	9.6	1.	.4	11.2	85.66

CUT DESCRIPTION: FN MLL RB ' FLNG TP SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1'DIA X 2' X 4FL X .12CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.0000 AXIAL DEPTH(IN): .100
LENGTH METAL CUT(IN): 166.70 EXTRA TRAVEL(IN): 13.00 RAPID TRVS DIST(IN): 228.10
VOLUME METAL CUT(CU IN) 16.67 VOLUME AIR CUT(CU IN): 1.30

M0: 1.629 M1: 17.970 M2: 50.010
K0: .567 K1: 4.043 K2: 286.613

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.006	52.4	30.0	0	0.00	0.00	.37	.61	7.81	.78	10.36	8.74	0.00	28.67	42.5	1.	.5	.9	573.44
.006	52.4	60.0	0	0.00	0.00	.37	.61	7.81	.39	5.18	4.37	0.00	18.71	40.8	1.	.5	1.7	374.54
.006	52.4	90.0	0	0.00	0.00	.37	.61	7.81	.26	3.45	2.91	0.00	15.41	40.2	1.	.5	2.6	308.26

CUT DESCRIPTION: FIN MLL PERIPH SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1'DIA X 2' X 4FL X .12CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .1000 AXIAL DEPTH(IN): 1.000
LENGTH METAL CUT(IN): 122.60 EXTRA TRAVEL(IN): 6.90 RAPID TRVS DIST(IN): 124.40
VOLUME METAL CUT(CU IN) 12.26 VOLUME AIR CUT(CU IN): .69

M0: .889 M1: 12.950 M2: 36.780
K0: .210 K1: 2.914 K2: 210.790

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.007	52.4	30.0	0	0.00	0.00	.20	.28	4.92	.49	6.53	5.51	0.00	17.94	26.2	1.	.6	1.4	358.73
.007	52.4	60.0	0	0.00	0.00	.20	.28	4.92	.25	3.27	2.76	0.00	11.67	25.1	1.	.6	2.7	233.36
.007	52.4	90.0	0	0.00	0.00	.20	.28	4.92	.16	2.18	1.84	0.00	9.58	24.7	1.	.6	4.1	191.56

CUT DESCRIPTION: FIN MLL RADII SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1"DIA X 2" X 4FL B/N .02 UNDERSIZE END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): 1.0000 AXIAL DEPTH(IN): .100
LENGTH METAL CUT(IN): 23.70 EXTRA TRAVEL(IN): 10.30 RAPID TRVS DIST(IN): 123.60
VOLUME METAL CUT(CU IN) 2.37 VOLUME AIR CUT(CU IN): 1.03

M0: .883 M1: 3.400 M2: 7.110
K0: .199 K1: .765 K2: 46.156

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.005	83.4	30.0	0	0.00	0.00	.20	.36	.84	.08	1.31	1.02	0.00	3.81	6.6	1.	.6	8.1	76.28
.005	83.4	60.0	0	0.00	0.00	.20	.36	.86	.04	.65	.51	0.00	2.61	6.4	1.	.6	16.1	52.13
.003	83.4	90.0	0	0.00	0.00	.20	.61	1.39	.05	.73	.57	0.00	3.54	10.0	0.	.4	14.5	70.83

CUT DESCRIPTION: FIN MLL PKT FLOORS SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 1.25"DIA X 2" X 6FL X .09CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .6400 AXIAL DEPTH(IN): .830
LENGTH METAL CUT(IN): 833.10 EXTRA TRAVEL(IN): 36.30 RAPID TRVS DIST(IN): 246.80
VOLUME METAL CUT(CU IN) 442.54 VOLUME AIR CUT(CU IN): 19.28

M0: 1.763 M1: 461.825 M2: 1327.628
K0: .357 K1: 103.811 K2: 9758.067

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.007	52.4	30.0	0	0.00	0.00	.40	1.21	27.87	2.79	59.56	28.70	0.00	120.53	143.4	5.	3.6	.2	2410.68
.007	52.4	60.0	0	0.00	0.00	.40	1.21	27.87	1.39	29.78	14.35	0.00	75.01	137.2	5.	3.6	.5	1500.18
.007	52.4	90.0	0	0.00	0.00	.40	1.21	27.87	.93	19.85	9.57	0.00	59.83	135.2	5.	3.6	.7	1196.68

CUT DESCRIPTION: FIN MLL PKT WALLS SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: 3/4'DIA x 2' x 4FL x .09CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .0500 AXIAL DEPTH(IN): 1.000
LENGTH METAL CUT(IN): 473.00 EXTRA TRAVEL(IN): 42.70 RAPID TRVS DIST(IN): 306.50
VOLUME METAL CUT(CU IN) 23.65 VOLUME AIR CUT(CU IN): 2.14

M0: 2.189 M1: 25.785 M2: 70.950
K0: .493 K1: 5.802 K2: 368.979

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.006	49.1	30.0	.0	0.00	0.00	.49	1.60	17.73	1.77	20.25	18.96	0.00	60.81	96.0	0.	.3	.4	1216.27
.006	49.1	60.0	0	0.00	0.00	.49	1.60	17.73	.88	10.13	9.48	0.00	40.32	93.1	0.	.3	.8	806.40
.006	49.1	90.0	0	0.00	0.00	.49	1.60	17.73	.59	6.75	6.32	0.00	33.49	90.7	0.	.3	1.1	669.77

CUT DESCRIPTION: FIN-MLL CRNR RADII SD B
MACHINE TOOL: CINCINNATI 5-SPINDLE-40 DOUBLE GANTRY N/C PROFILER
CUTTING TOOL: .5'DIA x 2' x 4FL x .09CR NEW END MILL

SETUP TIME(MIN): 0.00 LOAD-UNLOAD TIME(MIN): 0.00 LOT SIZE: 20

RADIAL DEPTH(IN): .0500 AXIAL DEPTH(IN): 1.000
LENGTH METAL CUT(IN): 203.50 EXTRA TRAVEL(IN): 24.10 RAPID TRVS DIST(IN): 394.20
VOLUME METAL CUT(CU IN) 10.18 VOLUME AIR CUT(CU IN): 1.21

M0: 2.816 M1: 11.380 M2: 30.525
K0: .634 K1: 2.561 K2: 132.275

ON-LINE DATA ANALYSIS

FEED (IPT)	SPEED (FPM)	TOOL LIFE (MIN)	CUTNG FLD CODE	SETUP COST ($)	LOAD-UNLD COST ($)	RAPID TRVS COST ($)	EXTRA TRAVEL COST ($)	METAL CUTTING COST ($)	DULL TOOL REPL ($)	TOOL DEPR ($)	TOOL RESHP COST ($)	TOOL PRESET COST ($)	TOTAL PART COST ($)	TOTAL PIECE TIME (MIN)	SPDL HP RQD	METAL RMVL RATE (CIPM)	PARTS PER TOOL	TOTAL BATCH COST ($)
.002	52.4	30.0	0	0.00	0.00	.63	1.69	14.30	1.43	11.44	14.67	0.00	44.16	80.2	0.	.2	.5	883.21
.002	52.4	60.0	0	0.00	0.00	.63	1.69	14.30	.71	5.72	7.33	0.00	30.39	77.1	0.	.2	.9	607.85
.002	52.4	90.0	0	0.00	0.00	.63	1.69	14.30	.48	3.81	4.89	0.00	25.80	76.0	0.	.2	1.4	516.06

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